# Behind the Facade: Evaluating the Effect of Facade Design on Daylight Admittance and Perceptual Assessments

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Architecture)
in the University of Michigan
2019

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# Dedication

Eliana (Ellie) and Evan Keon, you bring so much joy and laughter to my life. I love you. This research is dedicated to you.

# Acknowledgements

This dissertation research wouldn't have been possible without the direct and indirect help of so many amazing people. I would like to thank:

Dr. Mojtaba Navvab, my major advisor, who not only encouraged me to explore the meandering paths that I found interesting during my research, but who also traveled the paths with me, guiding me every step of the way. Moji, thank you for encouraging me to find my passion in research and for all that you have done for me.

Dr. MaryCarol Hunter, my wonderful minor advisor, for her continuous guidance, support and encouragement. Your wisdom, knowledge and expertise have always been valuable to me. Thank you for being my advisor, mentor and someone who I will always look up to.

Dr. Peter von Buelow, for agreeing to be on my committee, for teaching me ParaGen, for our successful and fascinating collaboration, and for always putting a smile on my face.

Dr. J. Alstan Jakubiec, who has always been there for me, who has supported me since the day we met at Harvard in 2010. Alstan, thank you for being on my committee, for answering my endless emails, and most of all, thank you for being my friend. I value our friendship and I look forward to more collaborations.

Ian Ashdown, my sincere gratitude for your continuous guidance and for being a mentor to me. Thank you for sharing your wisdom and for your patience. The world, and more specifically the academic world needs more people like you. I appreciate your advice and your encouragement during the past few years.

Dr. Jan Wienold, my unofficial advisor and colleague who has supported my work. Thank you for always answering my questions even when you are so busy, reading my papers, and supporting me throughout.

Dr. Kynthia Chamilothori, my dear “invisible office mate” and amazing friend whose creativity, brilliance and rigor never ceases to amaze me. You are truly inspiring. Thank you for collaborating with me and supporting me during the last years of my research. I am excited to be on the same path with you.

Dan Weissman, my amazing colleague, mentor, friend, critic, supporter, …. Thank you for all that you have done for me. For listening to my crazy research ideas, nonsensical stories, editing my writings, and so on. I am forever grateful for your help and support.

Dr. Claire Zimmerman, our PhD director, who has been on my side year in and year out. Thank you for fighting the fight and for supporting our work. I couldn’t imagine a better director.

Dr. Linda Groat, I will always appreciate your support and encouragement. Thank you for introducing me to the world of Environmental Psychology and for collaborating with me on a wonderful research project. I look forward to more collaborations.

Omid Oliyan, my colleague and dear friend, who put my research first many times, answering my endless grasshopper questions. Thank you for your friendship, for hours of phone conversations about surviving the PhD life. I will forever cherish our memories.

To Sarah Knudsen, my patient, and talented editor. Thank you for being so flexible with my crazy schedule and for reading my work through all its revisions. For being so meticulous and for keeping my voice in the edited versions.

To my amazing family, friends, and colleagues: Naghmeh, Ashkan, Arash, Omid, Judy, Mike, Jessica, Steve, Holly, Hedieh, Hossein, Siobhan , Sarah, Alaa, Beheshte, Ehsan, Babak, Zahra, and Soroush, Matthew, thank you for being there for me, for your advice, for listening to my frustrations, for putting a smile on my face, for making my house into a home. The past six years were amazing because you were all part of it.

My mom, the selfless, passionate, supportive, incredible mother who has always put my needs first. Thank you for supporting me, for believing in me and for being a wonderful grandmother. I hope I can be as good of a mother to Ellie and Evan as you have been to me.

To my husband and my biggest supporter, Nathan Sawyer, thank you for always being on my side. For walking the walk, believing in me, for encouraging me, for your patience. None of this would have been possible without you.

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# Abstract

Creating and evaluating architectural spaces is a mixture of art, science and engineering. We know how to make spaces functional in terms of intended use, temperature, light levels, security, and energy efficiency, but our understanding of the qualitative aspects of spaces remains limited. Our knowledge regarding the relations between subjective reactions (sensory/perceptual experience) and physical stimuli is incomplete, with a disconnect between environmental values measured through simulation and users' sensory and perceptual experiences of the environment. It is critical to address how green design does not necessarily result in comfortable or aesthetically pleasant design.

The proliferation of digital tools for analysis and design has changed how buildings are created and their performance optimized. This shift in design thinking, in parallel with improved fabrication techniques, has created new opportunities for integrating complexity in response to building performance, thus radically reinventing architectural systems. For more than a decade, designers and architects have relied on performance criteria, such as light levels or energy demand, to assess the performance of their design, including the design and performance of building facades.

Building facades are undoubtedly one of the most challenging architectural elements to design, as the issues of aesthetics, performance and functionality must be integrated. A successful building interior depends heavily on the design of the facade, and on a juxtaposition of different spatial volumes and light conditions. Some buildings stimulate feelings of happiness, interest, excitement, while others stimulate disturbance, gloom and discomfort. Factors that strongly affects such feelings is the presence of natural light and darkness, which are the most difficult elements to design for.

Natural light has been one of the critical aspects of valued architectural spaces; it influences the ambiance and the overall atmosphere of the space and how occupants perceive the interior

environments. Many of the current lighting metrics focus on quantifying the amount of light on horizontal work surfaces, thus overlooking the importance of daylight perception, ambiance and the dynamic nature of natural light, as affected by facade design.

The focus of this study is on the design of building facades, their pattern, complexity, and effect on daylight distribution and occupants' visual impressions. The objective is to find ways to enhance the experience of built environment inhabitants through the integration of building science, technology and design.

Through a comprehensive study of current methods for perceptual assessment of light qualities, this research study introduced the application of a new approach from Environmental Psychology to architectural research—Conceptual Content Cognitive Mapping (3CM)—to find attributes that might provide better insight into the questions of light qualities. The 3CM method was used to survey the concepts people find relevant to their experience of daylight in an office environment. The attributes most commonly used to describe why respondents like natural light in their work environment were characterized by emotions, which are ambiguous and tremendously challenging to design for and assess.

To understand the effect of facade design geometry on daylight ingress and distribution, a novel simulation method is introduced in this dissertation. This method calculates the annual spatial illuminance and luminance distribution through building facades, providing hourly light values for a full year. Additionally, a feedback loop is designed, whereby simulation data can be traced back to the building facade, allowing further geometric improvement. This method of designing and evaluating functional building facades promotes the integration of formal building design with sustainable practices.

Lastly, an experimental study using 360° HDR renderings of office environments was conducted to gain insight into the effect of facade design and light distribution on the participants' subjective impressions. The effect of simulation choices such as, scene materials (color, grayscale, default materials) and level of detail related to the presence of furniture was evaluated in virtual reality (VR). The results indicate that the effects of both color and furniture are statistically significant on numerous attributes about the qualities of the interior and participants' perception of brightness. The overall preference for a space is related less to actual measured lighting values and more to the overall design of the environment.

The results of this research study highlight the importance of occupants' visual perception alongside current sustainable energy considerations. The desire to bring natural light into spaces is not merely to support tasks; it is also essential to human comfort. Therefore, we must recognize the importance of finding metrics and indices to evaluate daylight as it relates to the perceived brightness, spatial distribution, mood, and ambiance of a space.

The methods discussed in this study allow designers and architects to differentiate the performance of complex and intricate facade systems, to evaluate their effect on the spatial distribution of daylight, and consequently, the quality of architectural spaces. This research contributes a new way to create and evaluate building skins and allows designers to understand the effect of facade design on natural light propagation, so such designs can be adjusted for improved performance. This research pushes boundaries and engages in dynamic new debates regarding qualitative assessment of architectural environment in VR by creating three-dimensional scenes rendered in VR for user preference studies.

Keywords:

Facade design, sustainability, daylight distribution, virtual reality, simulation, brightness perception

# Chapter 1
# **Introduction**

*“A great building must begin with the unmeasurable, must go through the measurable means when it is being designed and in the end must be unmeasurable.”*

*Louis Kahn*

## 1.1 Background

A building’s facade and its skin play a critical role in both separating and connecting its occupants to the outside world. It is one of the most important components of the building, demarcating the boundary between outside and inside, between public and private, the interior and the urban space. While these terms are somewhat interchangeable, in this work, the term ‘facade’ will be used to describe the exterior walls, including the glazing, and ‘skin’ to describe the outer layer in which the facade is wrapped. Although the role of the building facade has remained the same over time, its function often exceeds the basic notion of sheltering its inhabitants from the harsh outdoor elements (heat, rain, sun, sound, insects) to a more complex, coordinated system of parts that not only controls the interior conditions, but also possesses cultural, experiential, spatial, political, and stylistic significance.

Building facades and skins have undergone a variety of paradigm shifts, influenced by the development of materials, advancement of technology and changes in regulation. The industrial revolution in the 19th century dramatically changed building facades (Saelens, 2002). The use of iron and glass proliferated in architecture, transforming the design, construction and the overall performance of building facades. Solid structures were replaced by skeleton frames, lifting restrictions on the height and width of buildings by using prefabricated elements. New possibilities and challenges gave birth to new design and construction ideas.

Prior to the use of glass in facades, the size of openings was minimized to control energy loss. The use of glass and skeleton frame structure made it possible for openings to be enlarged and open toward the sky. Window openings in building facades increased as exterior walls were liberated from bearing the building load. Interior spaces were transformed from dark interiors to more open, luminous environments.

However, ever since the first skyscraper—the Home Insurance Building in Chicago (Figure 1.1)—which used a steel structure and metal frame, issues of ventilation, radiation, airflow, and visual comfort have been important considerations in modern architecture.


*Figure 1.1: Exterior of the Home Insurance Building by architect William Le Baron Jenney in Chicago, Illinois, built in 1885 (see image credit page)*

With the development of active systems for cooling, heating and lighting, a decoupling of passive strategies and design materialized. The buildings of the modern era became heavily reliant on air conditioning to maintain occupant comfort (Rosen, 2011; Sisson, 2017). Glass buildings with active systems proliferated throughout the world, regardless of the climate of the site. Building skins that were once decorated, transformed into bare and repetitive planes (Schittich, Lang, & Krippner, 2006). Buildings became characterizable by their volumes, flat surfaces of glass, industrial materials and lightweight aesthetics devoid of any ornamentation

(Figure 1.2). The decoupling of the facades and the structural frame became common in architecture; under the influence of the International Style, modern style buildings with more void than solid spread around the world.

*Figure 1.2: Mies van der Rohe's 860-880 Lake Shore Drive, Chicago, USA. Built in 1951 (see image credit page)*

However, in the 1970s, with increased awareness of energy efficiency and oil crises, the size, form and intent of the building facade was once again questioned (Ackermann, 2002). The sustainable movement progressed, and the shift towards greater energy efficiency or ecological awareness fundamentally changed the design of building facades and skins. Building skins, once again, were differentiated, decorated, given an identity, a face, a character.

## 1.2 Building Facade Design

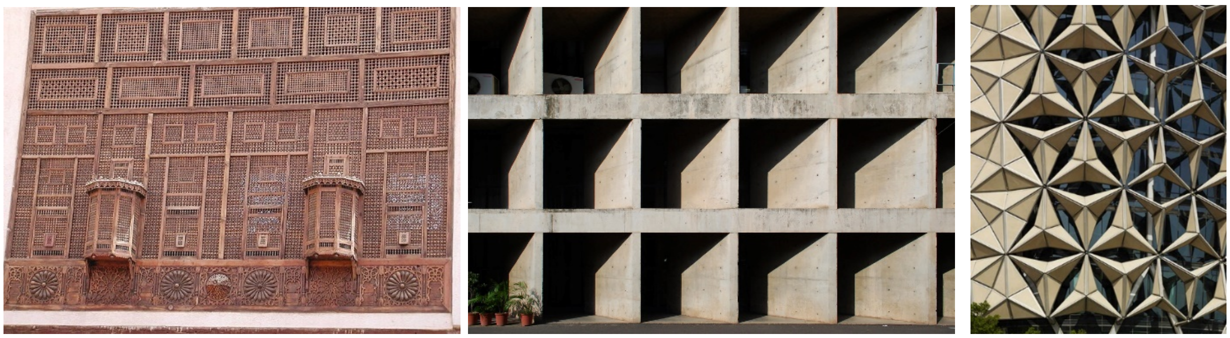
The design of building facades is a multi-faceted, complex process that focuses on the functionality and aesthetic performance of the facade and the ways in which the design sits within its site and context. Since the 1970s, the building facade has become a key element in efforts to conserve energy while optimizing for comfort. Its skin, shape, form, materiality, and thickness affect comfort-related factors such as lighting, ventilation, and temperature. With advances in technology, the design of building facades has become even more complex; they are expected to create highly controlled environments while simultaneously reducing energy consumption and maintaining occupants' comfort and satisfaction. In other words, facades must now achieve a multitude of significant functions beyond structural efficiency, including ventilation, lighting, insulation against heat and cold, protection against wind, glare, sun, noise, fire and humidity, all while conserving energy and connecting people to the outside world.

The increased use of glass in modern building facades, though beneficial for daylight infiltration in interior and visual access to the environment, goes hand in hand with the increased focus on shading surfaces to protect against direct radiation and to conserve energy associated with heat gains and losses through the facade. As thermal and visual comfort are reliant on light infiltration through the skin, the skin's geometry becomes an important design parameter for controlling direct sunlight. Controlling sun infiltration can be done using both internal and external shading systems. External shading systems are more effective as they block the radiation before it passes through the glass, and therefore buildings with external systems conserve more energy than those using internal blinds (Gratia & De Herde, 2007). Shading systems are essential in all buildings, especially those with high internal cooling loads, such as office environments.

The basic theory of sun control was well-known even to master builders and mathematicians in the second century A.D. (Cowan, 1966). However, increased interest in the topic started after the oil crisis of the 1970s, when people saw the direct relationship between sun control and the cost of energy used by air conditioning systems. The concept of shading systems design is not new in architecture, though such systems have transformed in style—ranging from the traditional decorated screens like mashrabiya (Figure 1.3a), to modern brise soleil (Figure 1.3b), and to a more integrated external skin of contemporary design (Figure 1.3c).

The design of building skins and shading systems can be challenging, as there are many factors that must be considered. In colder climates, it is important to admit adequate sunlight while controlling for glare and discomfort. In warmer climates, it is critical to exclude excessive heat—though summer heat load due to solar radiation can be problematic even in colder climates—while allowing adequate daylight to penetrate into the interior environments. Obstruction of the view is another important consideration, as views are often an important amenity in buildings. The technical aspect of blocking direct radiation using sun shading or the building's skin is relatively simple. Aesthetically, however, it introduces various challenges, as the skin becomes the most prominent element of the facade. Building skins are the most visible and complex elements of the architectural design process, and although there are many aspects that must be evaluated to judge the overall performance of the skin, among designers, its visual appearance is typically the first indicator of a good design. Therefore, much time and energy are spent on the design and aesthetics of the building skin—creating the layers, form, geometry and pattern.

The architecture of the postmodern era and present-day buildings, coupled with the advancement of modern digital tools, has brought about an array of complex and stylized building facades and skins.



*a) b) c)*

*Figure 1.3: a) Detail of mashrabiya, Maison es Suhaymi. Cairo, Egypt. Built in 1648*
*b) Carpenter Center for the Visual Arts, designed by Le Corbusier. Built in 1963.*
*c) Al Bahr Towers, designed by AHR. Built in 2012. (see image credit page)*

The proliferation of digital, computational or parametric modeling has also created a tectonic shift in the formation of building shapes. These have become standard tools in the work of architects. Digital and parametric tools are now inescapable in architectural pedagogy and the architectural milieu. The advancement of 3D modeling software, such as Rhinoceros, coupled with parametric modeling tools, such as Grasshopper and CATIA, has empowered designers to rapidly create, prototype and construct complex building skins and patterns. The complexity of skins in current buildings ranges from the overall form of the skin (Figure 1.4) to the geometrical pattern of window wall treatments (Figure 1.5).

*Figure 1.4: Undulating steel strips skin by Yoshihiro Amano (see image credit page)*

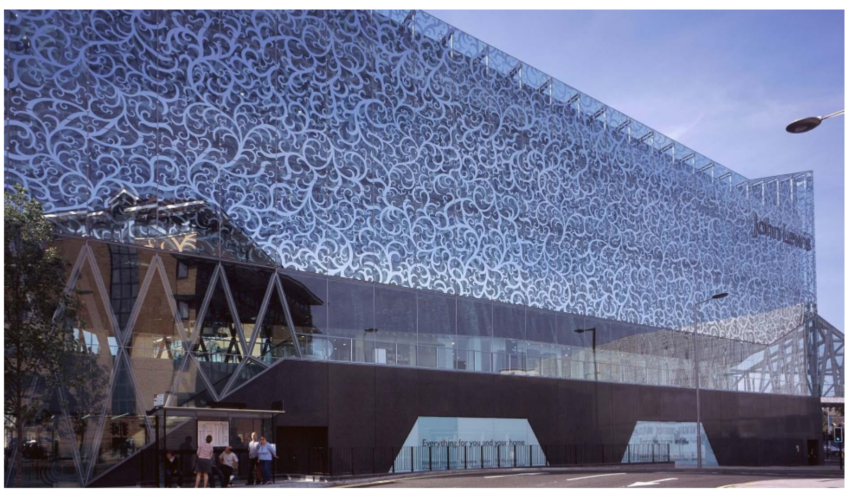



*Figure 1.5: John Lewis Department Store and Cineplex, Leicester. By FOA (see image credit page)*

Many contemporary skins are ornamental, i.e. lack environmental performance features such as radiation control. However, with the progressively increasing sophistication of digital and analytical tools to assess their behavior, there is an immense opportunity to make skins functional by carefully curating the parts that form the overall design and by integrating performance criteria into the skin design process. Digital tools have opened up new territories for design and tectonic explorations of form. The complex surfaces and skin patterns featured in contemporary buildings redefine the relationship between skin design and performance.

It is critical to underline here that the type, position and size of the openings in a building skin have a direct influence on its performance—specifically, on how the skin affects daylight distribution and infiltration. Therefore, one of the most important and challenging performance criteria for a building skin, one requiring special attention in the design process, is the ingress and distribution of natural light.

Natural light has both aesthetic and energy implications. Additionally, the design of the building skin and its influence on interior lighting has an impact on inhabitants, both physiologically and psychologically, although our understanding of the psychological impact of building skin design is still very limited (Chamilothori, Wienold, & Andersen, 2018). The design of a building skin is an intricate process that integrates art, science, engineering and craft to address an extensive and challenging list of issues.

## 1.3 Limitations of Current Methods to Assess Natural Light in Architecture

Natural light has always been valued among architects. Architecture depends on light to reveal its form, its meaning and intentions. For too long, the capabilities of light have been divided, either considered solely for aesthetic purposes by designers, or solely for providing visibility for specific tasks by engineers (Millet, 1996). The beauty of light is that it always simultaneously provides both aesthetic qualities and visibility. As the amounts of light in interior spaces are easier to measure, most metrics focus on the quantity of light and overlook the elusive and intangible qualities of daylight.

Access to daylight became a critical issue with the boom in construction of tall buildings and use of artificial lighting in the 1800s. The first profession to survey access to daylight started in 1865 (Ashdown, 2014). The first lighting metric, the Daylight Factor, defined as the ratio of the illumination on a horizontal plane inside to the exterior illumination, was initially introduced in 1895. In 1922, a judge in Great Britain adapted a daylight factor of 0.2 as the "border line" between adequate and inadequate lighting in a room (Cowan, 1966). In America in 1928, Harrison and Anderson proposed a simplified calculation method using horizontal illuminance values called the lumen method, which became the preferred method for measuring both natural and artificial lighting (Cowan, 1966; Cuttle, 2017; Kota & Habrel, 2009; Mardaljevic & Christoffersen, 2016).

Since then, we have moved from single point-in-time lux measures to more advanced annual metrics, such as Daylight Autonomy, which accounts for the influence of sky conditions and occupancy, and guides designers to understand the effect of their design on daylight ingress and energy reduction associated with a reduced need for electric lighting (Reinhart, Mardaljevic, & Rogers, 2006). Over the past two decades, there have been significant improvements in our understanding of "good" daylighting and increasing sophistication of metrics and simulation tools.

Most of the common metrics, though, have been developed with the goal of providing enough illumination for a particular task, as measured on a horizontal sensor plane, typically at desk level. Although climate-based illumination metrics are far better than point-in-time lux measurements or daylight factor, they also have many important shortcomings. Most common metrics used today, including climate-based metrics, reveal issues such as over- or under-supply of daylight in a space, but the values are not directly linked to the skin design and thus do not help designers use the measured values to adjust their design for better performance. This gap between light measurements and design must be addressed to capture the interaction between building skins and daylight.

Climate-based metrics can help designers to reduce the overall energy consumption associated with electric lighting usage; thus, they are important for energy considerations. However, most reduce the complexity of the lighting to a single value and overlook the influence of lighting on human health, visual comfort and the way in which occupants perceive spaces. In terms of building skin design, it is important for designers to understand the full behavior of the skin and how it filters daylight into spaces.

Another limitation of current lighting metrics is their use of a two-dimensional plane, assessing the amount of light that falls on it. We perceive our environments three-dimensionally, and light is perceived as a three-dimensional phenomenon—yet most methods that evaluate illuminance in interior spaces rely on a two-dimensional sensor plane. This two-dimensional plane, though beneficial for representing and understanding how much light falls on the desk plane, does not characterize our interior environments spatially and does not represent the quality of light and the way in which its distribution is influenced by the design of the building's skin. Rockcastle raised this issue by asking: "why are existing metrics still focused on non-perspectival, threshold-driven, and surface-based measurements?" (Rockcastle, 2017).

Another factor to consider when measuring light is the perceptions of occupants. "Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye. It is a quantitative science based on a statistical model of the human visual response to light—that is, our *perception* of light—under carefully controlled conditions" (Ashdown, 1994). Eyes' sensitivity varies with wavelength: a green light source appears much brighter to the human eye than an equivalent radiance in a blue or red spectrum. Similarly, the psychological and physiological state of the observer combined with other variables could change the eye's 'nonlinear response' to light (Ashdown, 1994). Therefore, if the goal is to design a performance-driven building skin, it becomes critical to understand how the skin's design and light penetration could impact occupant perceptions in interior environments.

## 1.4 Problem Statement

With the progressive sophistication of simulation and analysis tools there exists an enormous potential to influence the practice of architecture by enabling designers to fully understand the effect of their skin design on various aspects of sustainability, including human visual comfort and well-being. Horizontal, two-dimensional sensor planes inform designers if the required light levels are attained at 2.5 ft above the floor, roughly at desk-height. But to understand the three-dimensional spatial distribution of light infiltrating through the building skin, a new method is required, one that can move light simulation beyond two-dimensional surface planes.

Satisfying the basic requirements of task illumination while avoiding the visual discomfort associated with glare is an important goal but cannot be isolated from how lighting alters the appearance of the room. Additionally, there is a need to link values obtained from simulation to the design of the skin, so the data collected can inform further iterations of the design for better performance. Linking simulation values and skin design can help designers to understand the full behavior of their design, as well as how to efficiently adjust it to avoid over- and under-supply of light.

In addition to spatial light measurements, an understanding of light quality as impacted by the skin's geometrical pattern, and of the pattern's influence on occupants' perception and satisfaction is also required. There is a large body of research devoted to how we perceive light

(Cornsweet, 1970), but it is also important to understand what aspects of daylight are important to the occupants of office environments, and if and how the interior environment influences occupants' satisfaction with brightness. Cuttle wrote: "…when people in workplaces equipped with modern, efficient lighting complain about the lighting, their objections are likely to be directed towards the appearance of their surroundings. They may find the appearance of the workplace to be dull or gloomy, or the effect of the lighting to be harsh, producing dense unattractive shadows" (Cuttle, 2010). Can the appearance of the surroundings impact our light perception and satisfaction? And if so, how does that influence the design process and lighting research? Perhaps the answers to these questions will narrow the gaps between architectural design, lighting research and lighting design.

### 1.4.1 Thesis Objectives

I. To provide designers with a new technique to efficiently measure annual illuminance and luminance distribution through building skins.
II. To develop an automated procedure to connect simulated lighting data to a skin design so that areas of a design that are not performing well are identified for further adjustments.
III. To identify the aspects of daylight that are important to occupants in office environments, thereby providing a list of concepts that are relevant in qualitative daylight studies.
IV. To examine the impact of simulation choices on participants' subjective impressions.
V. To assess the influence of skin design and daylight distribution on participants' satisfaction with brightness.

### 1.4.2 Sections of the Research Study

*Section 1: Facade photometry*

This section introduces a technique to measure annual illuminance and the luminance distribution of daylight filtered through building skins. This section of research uses six diverse building skin designs, modelled in Rhinoceros and Grasshopper, to illustrate how the light distribution varies among different window treatments with geometrical patterns. The simulation is established as an automated procedure, such that when the skin is generated, a climate-based daylight simulation is initiated. After that simulation is completed, the simulated daylight values are linked to the skin design. The regions of the skin that allow ingress of daylight beyond a certain threshold are highlighted to provide a visual connection between the data generated and the design of the skin. This will allow the designer to adjust the design for better performance. Parts of this work have been published previously (Sawyer, 2017).

*Section 2: The use of Conceptual Content Cognitive Mapping (3CM) to identify daylight concepts that are important to occupants*

In this section of the research, Conceptual Content Cognitive Mapping (3CM), a survey methodology, is used to collect concepts that are relevant to daylight in office spaces. It uses participants' mental models and past experiences to highlight what aspects of daylight they like and dislike in their workspace. This section provides a list of concepts regarding daylight in work environments and emphasizes the concepts that should be considered in the design process.

*Section 3: The impact of color and simulation detail on subjective impressions of rendered scenes in immersive virtual reality*

Very little research has been devoted to investigating the influence of simulation choices, such as the use of colored materials and furniture, on participants' perception or appraisal of the environment. This section of research introduces an experimental study addressing this gap by examining the effects of simulation choices and level of detail in simulated scenes on participants' subjective impressions. This study uses a virtual reality headset to immerse participants in scenes of office spaces with differing skin designs. Through a verbal questionnaire, data was collected on participants' impressions of the scenes. This experimental study highlights the effect of both color and level of detail on participants' evaluations of the spaces, as well as the importance of these choices in experimental studies using visual stimuli.

*Section 4: Subjective impressions of a space influence brightness satisfaction: an experimental study in virtual reality*

The fourth section of this research introduces an experimental study in immersive VR to examine the effect of subjective impressions on brightness satisfaction. The aim of this section is to understand if participants' satisfaction with brightness is influenced by other variables (e.g. how the spaces are perceived in terms of their ambiance, pleasantness, whether they are considered exciting, calming, interesting, or complex) other than light levels. Participants responded to a verbal questionnaire while immersed in office scenes with differing skins. Skin designs ranged from simple horizontal louvers to complex geometrical patterns. The patterns of each design were modified to have the same perforation ratio of 40% to keep the brightness levels the same in all scenes. Thus, participants' ratings of their satisfaction with brightness in each space illustrate the influence of other perceptual attributes on participants' satisfaction with brightness. Parts of this work have been published previously (Sawyer & Chamilothori, 2019).

## 1.5 Thesis Structure

A broad historical overview of the importance of building skin design, both in terms of its aesthetic implications and environmental performance, was introduced in Section 1.1. In Section 1.2, various methods and metrics to measure daylight quantity were discussed. Key concerns and limitations were raised in Section 1.3 regarding common daylight measurements to highlight the importance of skin design due to its effect on daylight infiltration and distribution.

To situate the thesis topic within the broad area of research, an extended literature review and in-depth discussions of topics related daylight quantity and quality are presented in Chapter 2. Chapter 3 provides a broad review of the methodology, justification, and limitations of each method used in various experimental studies to address the objectives of the research study described in this thesis. Chapter 4 presents the four sections of the research study: first, a new technique to measure spatial annual daylight distribution is introduced. Second, a list of concepts related to the presence of daylight in office environments and deemed important and relevant by participants is presented. The list was generated by both architects and non-architects using a survey method commonly used in environmental psychology. A third experimental study examined the effect of simulation choices, such as the use of colored materials and furniture, on participants' perceptions. Lastly, the influence of the environment's perceptual attributes on the perception and brightness satisfaction of participants is presented. Chapter 5 concludes the thesis by summarizing and discussing the findings of the research program and suggesting areas of focus for future research.

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# Chapter 2
# State of the Art

This chapter will present a literature review of studies related to building facade performance, daylight measurements, and perceptual daylight appraisals using surveys and experimental studies in virtual reality. The aim of this chapter is to provide background on the topic of building facades and outer skins to situate their role in a larger context of building design, energy efficiency and occupant wellbeing. It will highlight some of the challenges and shortcomings of lighting research and provide perspective on the need to improve the body of knowledge in this area.

## 2.1 Building Facades and Skins

Building facades form the barrier between the interior space and exterior conditions. The facade is a physical component that encloses the space and controls its quality. It must be carefully designed to provide occupants with views of the outside world, insulate against heat and cold, protect against rain and moisture and control radiation infiltration and noise, all while allowing for ventilation and for natural light to enter the interior. Stylistically, its appearance situates the building in the larger context of the urban setting. Therefore, one could argue that the building facade is one of the most important components of the building design, as facades are key to achieving attractive, high-performance buildings (Chan & Tzempelikos, 2012).

The building facade, specifically its skin, dramatically affects lighting in interior spaces; a building's skin design can aid in exploiting daylight, and reducing its overall energy consumption. An important consideration in facade design is how the skin and exterior facade elements, such as the use of shading systems and light shelves, control light infiltration. The relationship between glazing, active and static shading systems, daylight penetration, views, radiation protection, indoor conditions and energy consumption have been widely explored, and exploiting daylight has been documented to lead to energy savings (Atzeri, Cappelletti, & Gasparella, 2014; Chan & Tzempelikos, 2012, 2015; Galasiu, Reinhart, Swinton, & Manning, 2005; Konstantzos et al., 2015; Laouadi, Reinhart, & Bourgeois, 2007; C. Reinhart et al., 2007). Notably, according to the U.S Energy Information Administration of the Department of Energy (www.eia.doe.gov), "Lighting is the largest single use of electricity in commercial buildings".

However, we have very limited knowledge about the relationship between facade design, light distribution and occupant satisfaction with brightness. Thus, the research described in this dissertation aimed to investigate the ways in which facades, skins and shading systems influence the interior spatial lighting distribution and occupants' perception and environmental appraisal.

It is widely accepted that daylight and visual comfort in an interior space contribute to occupant wellbeing, comfort and satisfaction (Aries, Veitch, & Newsham, 2010). Natural light has been shown to affect occupants' physiological and psychological wellbeing (Begemann, Van Den Beld, & Tenner, 1997; Boubekri, Mohamed; Hulliv, Robert B; Boyer, 1991; P. Boyce, Hunter, & Howlett, 2003; Farley & Veitch, 2001; Kittler, Kocifaj, & Darula, 2012; J. Veitch & Newsham, 1996).

Daylight is also an excellent resource for reducing overall energy consumption by displacing artificial lighting. However, when it is exploited, radiation control becomes critical, especially in warmer climates, and in commercial buildings such as offices, as it can adversely affect the cooling loads and occupants' visual comfort associated with glare (Huang & Niu, 2016; Lim, Zin Kandar, Ahmad, Ossen, & Abdullah, 2012; Manz & Frank, 2005). With the proliferation of window walls and energy crises, radiation is most often controlled using external facade elements such as shading systems. Daylight and radiation can be controlled by the building facade in three ways: by the overall form of the skin, including an additional layer of sun shading systems; by glazing technology, such as integrated shading systems, various Low-E coatings, and active systems (e.g. electrochromic glass); and by interior systems, such as internal blinds. The control of radiation and exploitation of natural light is an effective way to reduce the need for electric lighting and improve the overall energy consumption of the building (Nabil & Mardaljevic, 2006) and these are common strategies for passive design. The challenge, however, is to design the facade to minimize energy usage and visual discomfort associated with glare while maximizing daylight and preserving views of the exterior environment.

### 2.1.1 Evolution of Facade

The conceptual design section of the building facade is often the most important, as the decisions made during this stage greatly influence the overall performance of the building. Large glass enclosures provide substantial quantities of natural light (reducing the need for electric lighting thus saving energy) and views; however, too much light can cause overheating and can be a source of glare, leading the occupants to close the operable shades—a circular problem where there is excess heat but not natural light. On the other hand, reducing the window size can increase the use of electric lighting, thus increasing the overall energy consumption of the building. The use of overhangs, louvers, and fins as shading systems have allowed designers to control for solar radiation, but the use of these traditional systems have been limited in complex, postmodern buildings with sculptural skins (like that in Figure 2.1), as these elements cannot be easily integrated in the design.

With the advancement of modeling and parametric tools, there has been a surge in the number of complex building facades and skins. Most often, these facades are coupled with internal blinds, as their designs are not optimized for the best daylight and radiation performance. As previously stated, it is best to block radiation before it enters the building; therefore, internal blinds are not ideal shading systems for energy purposes. Complex sculptural skins (as seen in Figure 2.1) have the potential to go beyond aesthetic performance, to also provide shading while maximizing daylight infiltration. Over the last decade, there has been significant improvements in the design of building facades and skins to optimize their environmental performance (Adriaenssens et al., 2014; Bechthold, King, Kane, Niemasz, & Reinhart, 2011; Gugliermetti & Bisegna, 2006; Konis, K. and Selkowitz, 2017; Omidfar, 2011).

*Figure 2.1: An example of a complex building skin illustrating the difficulty of employing traditional shading systems such as overhang with these skins. Building: Suzhou Science and Cultural Arts Center. Studio 505. Architect Paul Andreu, Paris and ECADI, Shanghai—Facade Architect: dB(A)—Facade Engineer: ASSE Consultants (see image credit page)*

The process of designing and evaluating high-performance building skins that improve lighting and eliminate visual discomfort and direct radiation can be challenging and time-consuming. The typical process of designing such a building skin requires numerous iterations of the conceptual design based on simulation results (Kirimtat, Kundakci Koyunbaba, Chatzikonstantinou, & Sariyildiz, 2015). There are two major challenges inherent in the design of high-performance building skins: the first is related to measuring daylight infiltration through the design and using the measurements to improve the design; the second involves understanding how the facade and skin design—and its impact on light distribution—alters the perceptions and behaviors of a building's occupants.

Regarding photometric measurements, in most common lighting metrics, the data that are generated through simulations are not directly linked to the specific regions of the building skin, so it is unclear how to precisely and efficiently improve the performance of the design without entirely redesigning the skin. To situate this shortcoming in a larger context of lighting measurements, basic daylighting concepts and various metrics used in building codes and green building standards will be reviewed in the next section, followed by a review of the current literature on the impact of light on occupants' impressions, behaviors and satisfaction.

## 2.2 Research in Lighting

Lighting research can be broadly divided into two categories: photometric measurements and subjective assessments. Photometric measurements focus on quantifying the amount of light in a given space for task performance and for energy-related studies, while subjective assessments evaluate the quality of light (i.e. its color, intensity, distribution, uniformity) and its impact on occupants' satisfactions, impressions, cognition and behavior. While most scientific studies and lighting standards and recommendations prioritize lighting research related to visual performance and visual comfort, more and more qualitative research studies are bolstering the notion that following the recommended values and guidelines do not guarantee a good daylit environment, and suggest the need to further investigate the effect of light on occupants' mood, perception and well-being (Amundadottir, Rockcastle, Khanie, & Andersen, 2016; P. Boyce et al., 2003; P. R. Boyce & Cuttle, 1990; Cetegen , D .; Veitch , J . A .; Newsham, 2008; Cuttle, 2010; Heath, Jackson, & Goode, n.d.; Mahdavi & Eissa, 2002; Matos, n.d.; D. Tiller & Veitch, 1995; J. Veitch, Hine, & Gifford, 1993).

Veitch and Newsham suggested that "lighting quality exists when the luminous conditions support the behavioral needs of individuals in the lit space" (J. A. Veitch, 2001). Thus, the authors argued that the quality of lighting should be determined by balancing and integrating "individual wellbeing", "architecture" and "economics" (Figure 2.2). The following sections discuss the current methods used to assess light quality and the existing literature on the impact of light on users' perception and behavior.

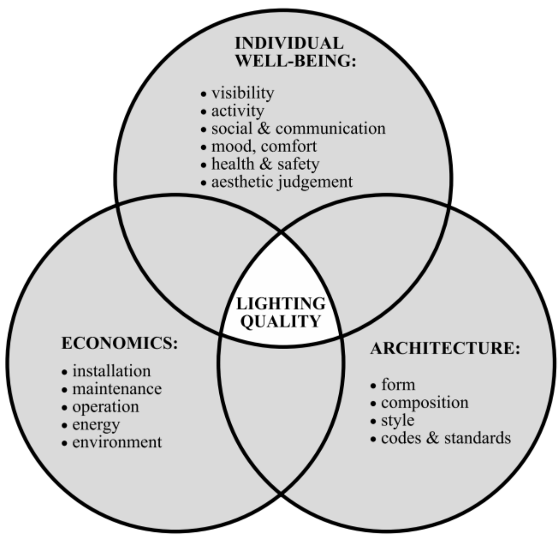


*Figure 2.2: Proposed diagram of "the integration of individual well-being, architecture and economics", from Veitch (2001)* (J. A. Veitch, 2001) *Copyright: National Research Council of Canada.*

### 2.2.1 Photometric Measurements

#### 2.2.1.1 *Common Daylight Performance Indicators*

The luminous environment is described by two units of lighting, illuminance and luminance. Illuminance is the amount of luminous flux on a surface per unit area. It is calculated based on the light source and the reflecting properties of surrounding surfaces. Illuminance is measured in footcandles (fc) or lux (lx). Luminance, on the other hand, is the luminous intensity reflected from a surface per unit area in a given direction. Luminance is measured in candela per square meter (cd/$m^2$ or nits). While illuminance is used to describe the amount of light on a given surface, luminance plays a key role in describing visual comfort associated with the glare, brightness levels and visibility in a given space (Figure 2.3).

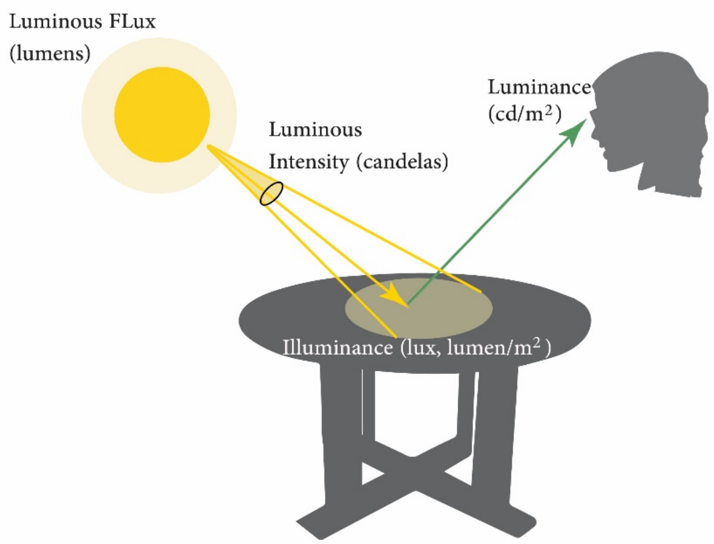


*Figure 2.3: Diagram of light properties—luminance vs. illuminance*

2.2.1.2 *From Static Illuminance-Based Measures to Climate-Based Metrics*

With the proliferation of tall buildings and electric lighting usage dominating indoor illumination, lighting measurements tools and methods have gained more attention in the last few decades. The first method used as a design tool was the Daylight Factor (DF) developed in England in 1922 (Cowan, 1966). DF is defined as the ratio representing the amount of light indoors relative to the available illumination outdoors under an overcast sky (Hopkinson, 1963). DF is defined with the formula:

$$f(x) = (\text{Indoor Illumiannce}) + \text{Outdoor Illuminance}) \times 100 \tag{1}$$

The DF formula represents the percentage of outdoor illuminance that falls on the indoor workplane. The recommended target levels are above 2%, with an upper limit of 6% (Ashdown, 2014; Waldram & Waldram, 1923). This method is one of the oldest, yet still one of the most common metrics used in lighting studies due to its simplicity and stability. An example of this metric is shown in Figure 2.4. However, because DF is always calculated under an overcast sky, it does not take into account realistic climate conditions, direct and reflected sun exposures, latitude, building orientation, date and time, or potential glare risk (Mardaljevic, Heschong, & Lee, 2009).

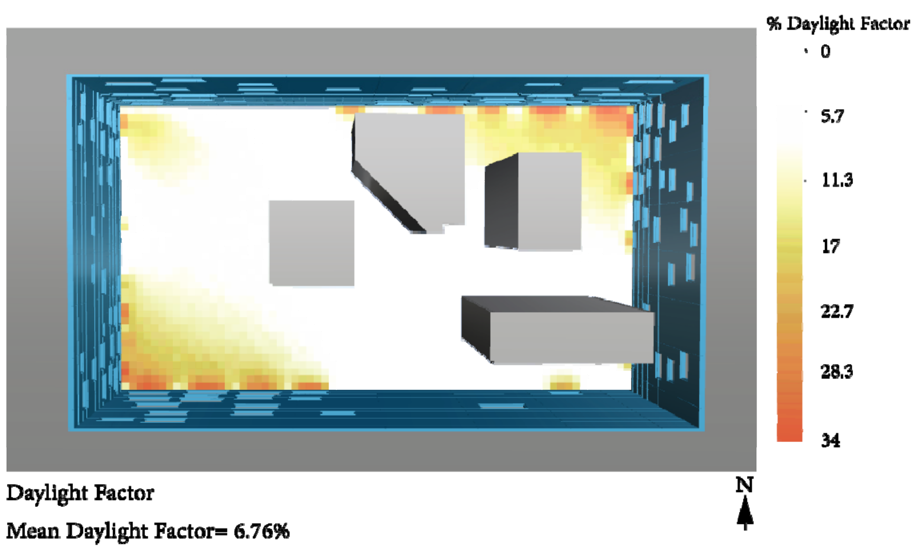


*Figure 2.4: An example of Daylight Factor analysis*

A few years later, in 1928, Harrison and Anderson introduced the lumen method, which enabled the effects of interreflected light to be considered in the calculation (Cuttle, 2010; Lam, 1992). This method is based on taking the average illuminance of a horizontal workplane that is raised from the floor to about the desk level, roughly 2.5–3.0 feet. The lumen method is defined with the formula:

$$\text{Lumens per lamp} = \frac{\text{footcandles x depreciation factor x area in square feet}}{\text{number of lamps x coefficient of utilization}} \quad (2)$$

Depreciation factor= Maintenance factor

Coefficient of Utilization= (utilization factor) “ratio of ‘useful lumens’ to the lamp lumens” (Cuttle, 2017). The coefficient of utilization is a function of surface reflectance and room proportions.

Since the development of the lumen method, the average illuminance that falls on the horizontal two-dimensional workplane has become the foundation of lighting standards and metrics (Cuttle, 2010). Over the past few decades, there has been a major shift in the development of metrics and analysis tools. The advancement of computer simulation tools, as well as access to improved computational capabilities and detailed hourly data, have allowed designers to move beyond point-in-time measurements (evaluating light at one time of a single day at a single condition) to measure daylight over the entire year. With these capabilities, the behavior of a complex facade and skin design can be evaluated relative to the variability of daylight throughout the year.

Thus, lighting metrics have transitioned from the DF and lumen methods, which are considered static illuminance-based measures to point-in-time illuminance calculation and then to annual climate-based metrics, such as Daylight Autonomy (DA) (C. F. Reinhart & Walkenhorst, 2001b), Continuous Daylight Autonomy (cDA) (Rogers, 2006), Useful Daylight Illuminance (UDI) (Nabil & Mardaljevic, 2006), Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) (Lee, Boubekri, & Liang, 2019). The transition to dynamic daylight performance metrics allows designers to calculate illuminance or luminance inside a building. They are based on time series that extend over the entire year, and take into account the annual solar radiation data of the building's location (C. F. Reinhart, Mardaljevic, & Rogers, 2006). Weather data can be accessed via the US Department of Energy, which offers data for thousands of sites worldwide (Crawley, Hand, & Lawrie, 1999). Dynamic climate-based analysis metrics utilize time-varying sun conditions and sky to predict hourly levels of daylight illuminance. While static metrics such as DF produce a single value, dynamic climate-based metrics illustrate the illuminance prediction for every hour of the year for each sensor point (Nabil & Mardaljevic, 2006). The progression of lighting metrics and tools, illustrating the advancement in technology for digital lighting calculations and improvement in general understanding of the importance of lighting in interior environments, can be seen in Figure 2.5.

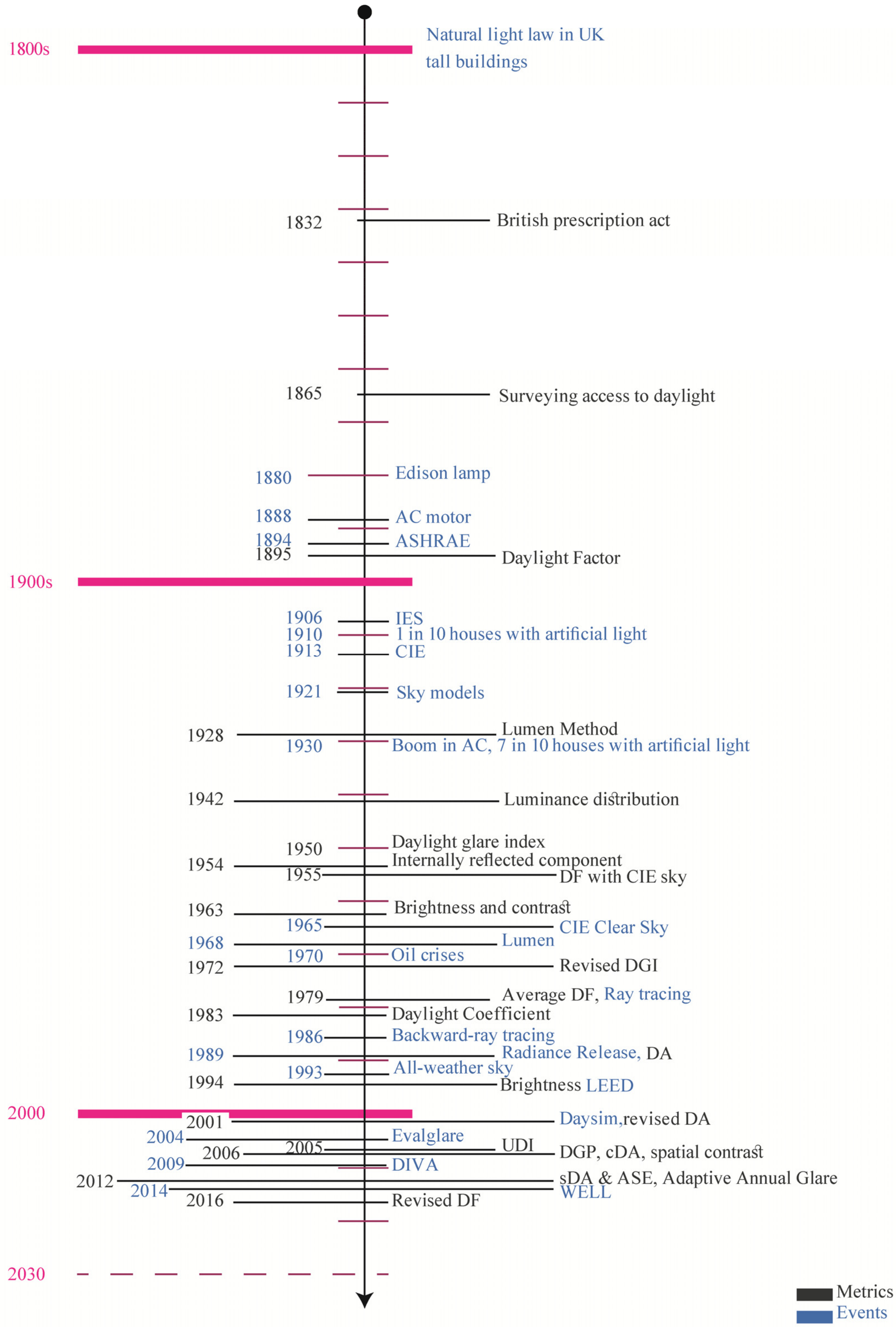


*Figure 2.5: Progression of metric and tools from 1800–2017*

2.2.1.3 *Daylight Autonomy*

Daylight Autonomy (DA) is the percentage of occupied time that the desired illuminance level is achieved at the sensor plane by daylight alone (C. F. Reinhart & Walkenhorst, 2001a),(Reinhart, F, Mardaljevic, & Rogers, 2013). DA is a dynamic climate-based metric which considers specific weather condition and geographic location on an annual basis (C. F. Reinhart & Walkenhorst, 2001a),(Reinhart, F et al., 2013). When running a DA simulation, users can set a specific threshold at which DA is calculated. For example, if a DA threshold of 500 (lux) is set, the results represent the percentage of the sensor plane that exceeds 500 lux at least 50% of the time. An example of DA analysis is shown in Figure 2.6.

It is important to note that this method only counts sensors that exceed the required level and does not count those below the set value. Another limitation of DA is that it does not demonstrate the amount by which the set value (recommended by IES standards) was exceeded at a particular instant or sensor point, which can result in high illuminance levels that could potentially cause thermal and visual discomfort (Nabil & Mardaljevic, 2006).

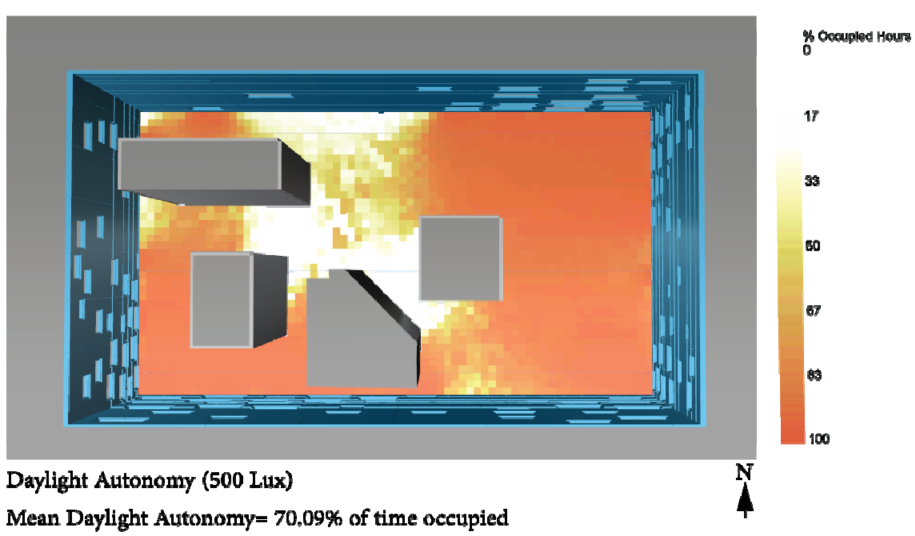


*Figure 2.6: An example of DA analysis. The building in this example is located in Chicago (41.98 N/87.92 E).*

2.2.1.4 *Continuous Daylight Autonomy*

In 2006, Continuous Daylight Autonomy (cDA) was proposed by Zack Rogers. Since DA does not give credit to daylight sensors that are partially daylit, Rogers proposed to give partial credit to sensors that contribute to the daylight in the room, even if they are below the set value. For example, if a sensor receives 100 lux of daylight illuminance and its required illuminance is 500 lux, the sensor is partially credited, 100 lux/500 lux, or 20% daylight, for that time (Rogers, 2006). An example of cDA analysis is shown in Figure 2.7.

Like other metrics, cDA has a few limitations. First, it does not clearly highlight the hours where there could be problems; second it is not appropriate for comparing multiple design options, as the same value of cDA could represent two very different lighting scenarios.

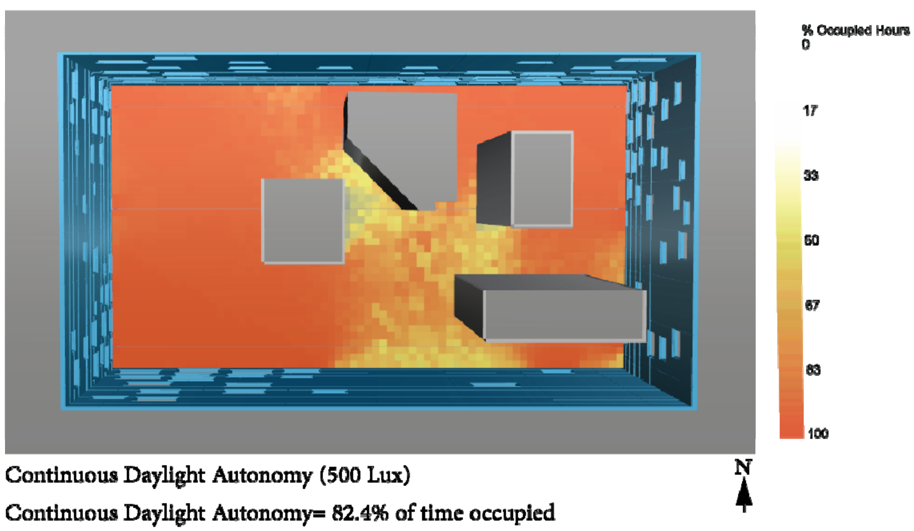


*Figure 2.7: An example of cDA analysis. The building in this example is located in Chicago (41.98 N/87.92 E).*

2.2.1.5 *Useful Daylight Illuminance*

Another dynamic climate-based metric is the Useful Daylight Illuminance (UDI) introduced by Mardaljavic and Nabil (Nabil & Mardaljevic, 2006). In contrast to DA which measures how often a minimum threshold is maintained by daylight alone, UDI measures how often in a year daylight illuminances within a “useful” range is achieved at each sensor point (Nabil & Mardaljevic, 2006). When UDI was first introduced, it used three illumination ranges—0–100 lux, 100–200 lux, and over 200 lux—though full credit was given to values between 100 lux and 2000 lux, suggesting that anything below 100 lux is not useful and above 2000 lux is undesirable due to the potential for glare or overheating. The authors proposed to consider the useful daylight illuminance that occurs whenever the illuminance values at each sensor point fall within a range of 100–2000 lux. In 2012, UDI was updated to have five thresholds: less than 100 lux (fell short), greater than 100 but less than 300 lux (supplemental), greater than 300 but less than 3000 lux (autonomous), greater than 100 but less than 3000 lux (combined) and greater than 3000 lux (exceeded) (Mardaljevic, Andersen, Roy, & Christoffersen, 2012). An example of UDI (100–2000 lux) is shown in Figure 2.8.

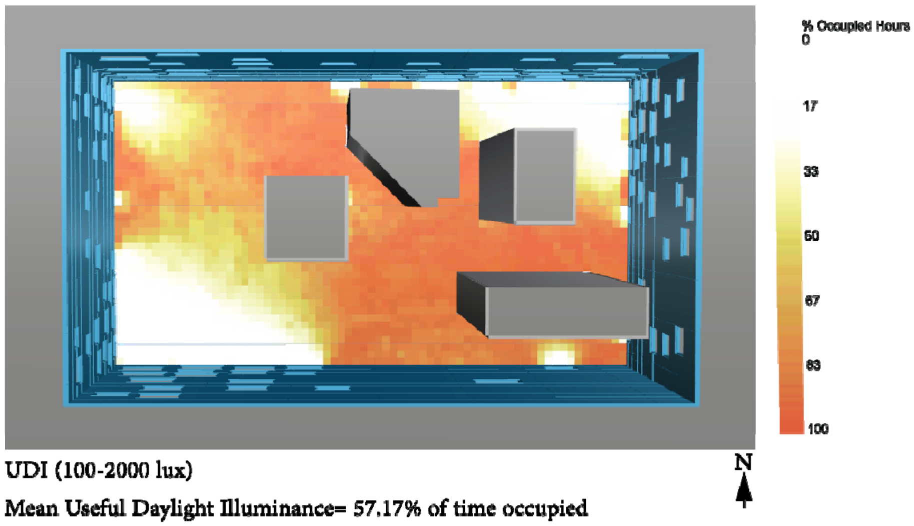


*Figure 2.8: An example of UDI analysis. The building in this example is located in Chicago (41.98 N/87.92 E).*

2.2.1.6 *Spatial Daylight Autonomy and Annual Sun Exposure*

Spatial Daylight Autonomy (sDA), a metric developed by the IES Daylight Metrics Committee in 2012, is defined as the percentage of floor area that is above 300 lux for a minimum of half of all occupied periods (Illuminating Engineering Society & The Daylight Metric Committee, 2013). sDA uses a climate file and an algorithm to approximate the manual operation of window blinds. Annual Sunlight Exposure (ASE) is defined as the percentage of the area that receives at least 1000 lux of direct sunlight for more than 10 percent of the year or 250 hours a year (Lee et al., 2019). ASE can help designers limit excessive direct sun in a space. The sDA and ASE metrics are intended to be used together (Illuminating Engineering Society & The Daylight Metric Committee, 2013); thus, designers should aim to achieve higher sDA values while minimizing the ASE value (to less than 10 percent). Examples of sDA and ASE analysis are shown in Figure 2.9 and Figure 2.10, respectively.

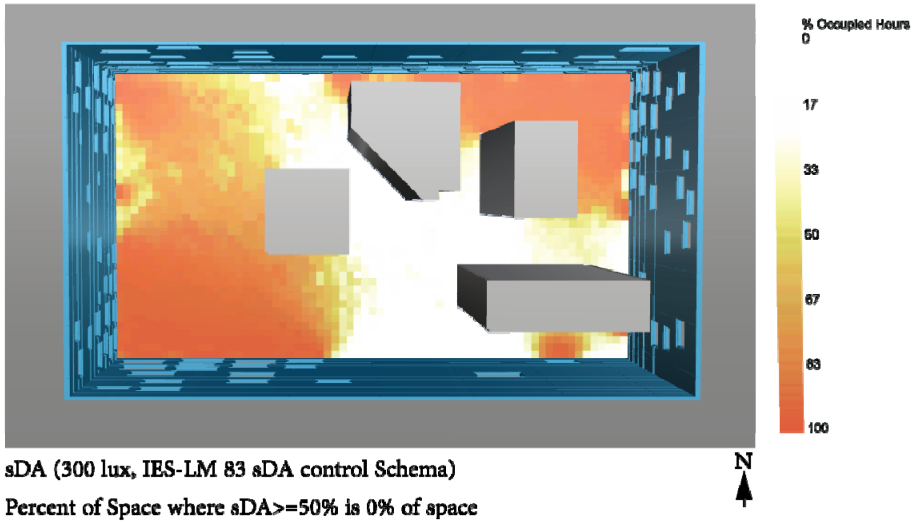


*Figure 2.9: An example of sDA analysis. The building in this example is located in Chicago (41.98 N/87.92 E).*

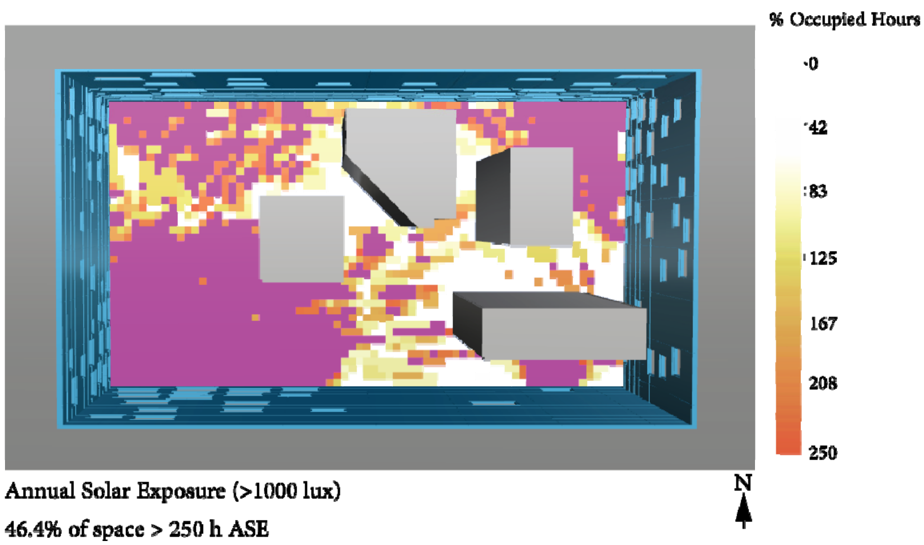


*Figure 2.10: An example of ASE analysis. The investigated building is located in Chicago (41.98 N/87.92 E).*

### 2.2.2 Subjective Impressions in Lighting Research

The common metrics for predicting the effect of daylight on building performance focus on the amount of illumination following standards and recommendations for task performance. These recommendations have reduced lighting for illumination to values that are not related to how spaces are perceived by users (Lam, 1992), and following these recommendations may not produce environments with good lighting quality (P. R. Boyce & Smet, 2014). The literature in the field shows light has a significant impact on occupants' satisfaction, emotional response, behavior and wellbeing.

Lighting is one of the most important features of interior environments. It is not only desired because it allows us to see our surroundings, impacting our visual comfort and wellbeing, but it also influences how we perceive our environment. The impact of lighting on occupants' perceptions has been broadly recognized and discussed in the field of architecture (Holl, Kwinter, & Safont-Tria, 2011; Pallasmaa, 2012; Zumthor, 2006). Although a large body of research has been dedicated to the relationship between the ingress of light and energy savings (Chan & Tzempelikos, 2015; Galasiu et al., 2005; Mardaljevic et al., 2009; Shen, Hu, & Patel, 2014; Veitch, Jennifer a., Newsham, 1997), the effect of light on occupants' perceptions must not be overlooked, as it affects their behavior and overall satisfaction with the environment (J. A. Veitch, 2001). While there is a considerable amount of research on the effect of light on visual performance (Atzeri et al., 2014; Cuttle, 2010; Motevalian, 2014; Shen et al., 2014; Veitch, Jennifer a., Newsham, 1997), the effect of luminance distribution on our behavior, mood and satisfaction have not yet been extensively studied.

In the 1970s, the Buffalo Organization for Social and Technological innovation (BOSTI) conducted a survey study of over 10,000 office workers in the United States. The aim of the research was to understand the effect of environmental factors on occupant's performance, environmental satisfaction and job satisfaction. The impact of lighting on occupant's performance, job satisfaction and environmental satisfaction was listed among the key findings. Occupants' control over lighting impacted their satisfaction, but only visual discomfort affected their performance. The amount of lighting was also listed as a factor that directly affected occupants' job satisfaction and performance (Isacco, 1985).

Louis Harris and Associates conducted a similar survey study for Steelcase in 1980, to gain insight into the effects of office environment on workers productivity. They asked 1207 workers what factors they thought would affect their productivity in the workplace. The results indicated that 74 percent of workers believed that their productivity would be increased by improved working conditions. "Good lighting and comfortable chairs were the highest ranking factors which affected comfort in the mind of the participants" (Isacco, 1985).

In 1973, Flynn and his colleagues conducted an interim study to investigate the impact of light on impression and behavior (J. E. Flynn, Spencer, Martyniuk, & Hendrick, 1973). They altered the appearance of a conference room by using six different lighting configurations and asked observers to make a subjective assessment of the lighting. Three main factors—perceptual clarity, spaciousness and pleasantness—were used to assess the subjective impression of the luminous environment. They obtained ratings on 34 semantic differential scales and used factor analysis and multidimensional scaling to identify different dimensions of lighting that impact occupants' subjective impressions, namely peripheral and overhead lighting, uniformity, and brightness. Their experiment showed that people prefer lit environments that appear "bright" and "interesting". In later studies, brightness is used as an attribute that is linked to the perception of “spaciousness”, and “interesting” is related to light uniformity (Houser, Lc, Fies, & Mistrick, 2002; Loe, Mansfield, & Rowlands, 1994; Paredes, 2016; J. A. Veitch, 2001) .

Later, in 1979, they published a guide presenting techniques and the procedures for measuring subjective impressions in lighting, signifying that “human responses to spatial lighting patterns are, in some extent, shared experiences” (J. Flynn, Hendrick, Spencer, & Martyniuk, 1979). Flynn and his colleagues used psychological techniques and statistical analyses to examine the influence of light on how spaces are perceived. They used lighting design as a “vehicle” to impact the information processes of the visual field.

Around the same time, in 1979, Hawkes et al. completed a survey of 28 participants in a two-person windowless office with 18 different lighting configurations (Hawkes, Loe, & Rowlands, 1979). The aim of the study was to gain insight into the questions of lighting quality and perception. The authors reported that participant’s perception can be described by factors of brightness and interest—factors that can also be described by lightness and variability. In another study, Loe et al. (1994) explored the connection between physical measurement of average luminance and luminance contrast and subjective assessment of lighting using semantic differential scales. In this study, the authors altered the lighting conditions of a conference room in 18 different ways. Using factor analysis, they identified two main factors, “visual lightness” and “visual interest”. “Visual interest” was found to be related to non-uniformity (the more non-uniform the light pattern the more interesting and pleasant the space was perceived), while “visual lightness” was related to “spaciousness”. These factors directly related to the luminance within a horizontal band 40 degrees wide and centered at the normal eye height of a seated observer. Furthermore, the results of their study showed that the scale of “visual lightness” is highly correlated with the log of the average luminance of the horizontal 40-degree band and the log of ratio of maximum to minimum luminance was highly correlated to the scale of “visual interest”. The authors concluded that high ratings for one factor is insufficient, because participants desire lit environments to be *both* “interesting” and “light” (Loe et al., 1994).

One of the common results among the studies discussed above is that brightness and interest (luminance and non-uniformity or variability) are found to be the two main dimensions describing the lit environment. However, Veitch and Newsham published a study of lighting quality in which they concluded that the three factors of “visual attraction”, “complexity” and “brightness” explained only 46 percent of the variance (Veitch, Jennifer a., Newsham, 1997). They installed nine lighting systems in a windowless open-plan office space with six workstations. A total of 292 subjects participated in the study by working one full day under one of the nine lighting conditions. Unlike previous studies, where the participants were asked to judge the lighting in the space, in this study, participants were asked to judge the appearance of the room rather than the lighting. This could be why this study’s results do not align with those of previous studies. Judgments of the aesthetic appearance of the room were analyzed using 27 semantic differential pairs. Despite the large sample size, the values were not significant, and no meaningful effects were detected.

In 2000, Knez and Kers conducted an experimental study to evaluate the impact of lighting, gender, and age on mood and cognitive performance (Kenz & Kers, 2000). Using an office room with false windows, they interviewed 80 subjects under two different lighting conditions: warm white light (3000 K, emitting a more reddish light), and cool white light (4000 K emitting a bluish light). The experiment required participants to self-report their aesthetic, affective state of mood, to complete a questionnaire evaluating the lighting and estimating the perceived light, and to perform cognitive tasks. The authors noted that the light in the room impacted the mood of participants. However, the results showed that the effects varied by participants' age and gender. The authors concluded that indoor lighting can alter the emotional meanings that are conveyed to occupants.

In 2008, Vogels developed a questionnaire to evaluate a space in terms of its affective appraisal or atmosphere (Vogels, 2008). The results of her study revealed that four dimensions can describe the atmosphere of a space: "coziness", "liveliness", "tenseness", and "detachment". In a later study, light intensity showed to decrease the perceived "coziness" and "tenseness" and significantly increase "liveliness" and "detachment" (Vogels, de Vries, & van Erp, 2008). In fact, studies show a clear relationship between brightness and perceived uniformity on all four dimensions of perceived atmospheres (M. Stokkermans, Vogels, de Kort, & Heynderickx, 2017).

The existing literature suggests that participants' subjective impressions are influenced by the brightness, luminance distribution and lighting patterns of a space (Houser et al., 2002; Ne'eman, Craddock, & Hopkinson, 1976; Rockcastle, Amunddadottir, & Andersen, 2016). Previous studies also suggest that areas with indirect and non-uniform lighting are perceived as more spacious (Houser et al., 2002).

Similarly, the perceived brightness of a space is influenced by light uniformity. In an experimental study to evaluate the impact of luminance distribution in an office space with artificial lighting, the results revealed that non-uniform lighting makes the environment appear brighter and requires 5–10 percent less illuminance on the working plane compared to an identical space with uniform lighting distribution (D. K. Tiller & Veitch, 1995). This suggests that our brightness perception and satisfaction is also altered by factors other than light levels, such as light uniformity.

2.2.2.1 *Daylight vs. Artificial Lighting*

Although most of the aforementioned scientific studies addressed the effect of lighting on occupant perception and subjective impressions, with a few exceptions, they focused on artificial lighting, not daylighting. Daylight is vastly different than artificial lighting, not only in terms of light intensity, color and spectrum, but also in that it is a dynamic source and its variability impacts how occupants appraise spaces.

In a survey study aimed at understanding user preference for lighting, Veitch et al. concluded that a majority of university students (~78%) believed that daylight was better than artificial light, and in fact believed that fluorescent lighting can have a detrimental effect on their health (J. Veitch et al., 1993). Similarly, Christopher Cuttle interviewed 471 office workers to understand their preferences regarding windows in the work environment. The results of the study indicated that 99 percent of participants believed that the workplace should have windows and 86 percent choose to work in daylight rather than with an artificial light source. The author noted that participants believed that artificial lighting could negatively affect their health (Paredes, 2016). In another research study of the evaluation of "pleasantness" in an environment with three sources of lighting (artificial, daylight and combined lighting), the authors concluded that environments with only daylight were considered "pleasant" (Laurentin, Bermtto, & Fontoynont, 2000).

People prefer a daylit space, and their evaluations of that space and its aesthetics are more positive with daylight (Moscoso & Matusiak, 2015). There are different aspects of daylight that can alter how spaces are perceived—its color temperature, dynamics and intensity—which is why it is difficult to exactly isolate what aspects of daylight impact users' perceptions, and how its presence influences their appraisal of the environment. It is clear that daylight alters the spatial luminance distribution and light intensity, and because it is often associated with a view to the outside world it can influence the subjective impressions of the occupants.

Therefore, the impact of window size, views, daylight variability, sun infiltration and shadows cannot be overlooked when designing with daylight, as they influence how the spaces are perceived and alter the ephemeral qualities of the indoor lighting (Ne'eman. E; & Hopkinson, 1970).

2.2.2.2 *The effect of windows, views and sunlight on participants' perceptions*

In 1976, Ne'eman et al. conducted a survey study of four different types of buildings (housing, schools, offices, and hospitals) to examine if occupants in these types of environments desire sunlight, and to determine the effect of sunlight on their assessment of indoor environments (Ne'eman et al., 1976). The authors noted that people desire sunlight for its thermal, visual, and psychological effects.

Sunlight influences how spaces are perceived in terms of pleasantness, adds sparkle and brilliance to the environments, and frees them from "gloominess" and monotony. Daylight connects people to the exterior environment. It enhances the contrast and colors and reveals forms and textures. It also provides the feeling of warmth (Lam, 1992; Ne'eman et al., 1976). The results of the study indicated that sunlight significantly impact individual's assessment of the indoor environments and the non-physical properties of sunlight influence occupants' psychological wellbeing. Previous studies have also suggested that sunlight increases the perceived pleasantness and warmth of a space among its users (Wang & Boubekri, 2011).

In 1991, Boubekri et al. studied the impact of window size and sunlight penetration on individuals' mood and satisfaction in an office space (Boubekri, Mohamed; Hulliv, Robert B;

Boyer, 1991). Unlike the previous study of Ne'eman et al., who measured the duration of sunlight in indoor spaces, this study focused on the duration and the size of the sunlit area in the room as visual stimuli. Four window-to-wall ratios—10%, 20%, 40% and 60%—were used to alter the size of the sun patch on the floor area. The results indicated that sunlight penetration significantly impact an individual's assessment of the environment, particularly the feeling of "relaxation" (described by attributes of "calm", "relaxed" and "peaceful"). They concluded that the optimum size of sunlit areas in the room should be above 10% and ideally below 40% to promote feelings of relaxation. Categen et al. found similar, though less quantitative, results using a survey to assess the effect of view size and luminance on employee satisfaction (Cetegen , D .; Veitch , J . A .; Newsham, 2008). By interviewing 36 participants, they concluded that employee satisfaction with the amount of "view", "visual comfort" and "pleasantness", as well as "spaciousness", increased with luminance and the size of the view to the outside.

In 2011, Wang and Boubekri published a list of recommendations based on the cognitive performance, mood and presence of users in sunlit work environments (Wang & Boubekri, 2011). They established a method to improve daylighting design based on behavioral approaches, including emotional, attitudinal and cognitive responses of participants in various sunlit conditions. Their study used a multifunctional seminar room with a window wall facing east and with an outdoor view of a natural landscape. Ten different seating locations in the room were examined—two in a sun patch area, two on the boundary of the area, three 4.0 feet away from the sun patch, and three 8.0 feet away from the sun patch area. The participants were asked to first rate their mood, then complete cognitive tasks (reading and analogy tasks) and rate their mood once more after completing the tasks. This study confirmed the results of previous studies, finding that participants preferred to sit close to the window and the sun patch. However, the authors noted that glare was a common concern among the participants. The statistical analysis results also showed that sitting location had a significant effect on subjects' performance, on both the reading and analogy tasks. Regarding mood, participants who were close to the sun patch and had a better view of the outdoors showed less mood decrease than those far from the sun patch and the window.

Daylight has also been shown to affect the satisfaction and behavior of university library users (Kilic & Hasirci, 2011). The results of one study indicated a significant relationship between daylight and user behavior, specifically seating preferences, in school libraries. More than 56 percent of users preferred seating areas near windows for studying. The authors noted that daylight significantly impacted the amount of time users would spend in one place within the library, and they found a strong relationship between daylight and perceived comfort. Additionally, the total amount of light altered the perceived "spaciousness" (Kilic & Hasirci, 2011).

Because daylight is often connected with a view of the outside world, it is hard to separate its effects on the observer's appraisal of the environment. In one study where participants only saw the diffuse daylight in the space without having a view of the outside, daylight showed no significant effect on the perception of light and uniformity and the perception of atmosphere (M. G. M. Stokkermans, Chen, Murdoch, & Vogels, 2015). The authors argued that this result was due to the fact that participants only viewed diffuse lighting, not direct lighting, and therefore the effects on luminance and contrast were small. However, an alternative takeaway could be that this result is not due to the lack of direct lighting and is instead primarily due to the absence of view, suggesting that presence of view alters the perception of light and brightness. It has also been suggested that our evaluation of luminous environment is more affected by other factors, such as the size of a window (Moscoso & Matusiak, 2015), natural scenes, and presence of water rather than light levels in the room (Tuaycharoen, Barch, & Mcibse, 2005; Tuaycharoen & Tregenza, 2007).

2.2.2.3 *Experimental studies of subjective impressions in lighting research*

With advances in technology and the proliferation of accurate physically based simulation and computer-generated visualizations, lighting research has moved from field studies to the use of immersive virtual reality (VR). Virtual reality has been implemented as a research tool in various fields, including psychology, medicine and architecture, to study issues related to depth perception, presence and emotions, visual perception, construction, user behavior, modeling, briefing clients, spatial colors on perception, spatial memory, decision making, distance estimation, and experience of indoor spaces, among others (Armbrüster, Wolter, Kuhlen, Spijkers, & Fimm, 2008; Dilworth, 2010; Franz, Von Der Heyde, & Bülthoff, 2005; Hall, Navvab, Maslowski, & Petty, 2012; Kuliga, Thrash, Dalton, & Hölscher, 2015; Lekan, 2016; Loomis, Blascovich, & Beall, 1999; Paes, Arantes, & Irizarry, 2017; D. R. Patel, 2017; N. K. Patel, Campion, & Fernando, 2002; Patterson, Darbani, Rezaei, Zacharias, & Yazdizadeh, 2017; Riva et al., 2007; Schuemie, van der Straaten, Krijn, & van der Mast, 2001; SIAMIONAVA, 2016; Westerdahl et al., 2006; Woksepp & Olofsson, 2008).

The use of VR in the field of lighting and evaluation of subjective impressions has surged in the last few years. VR provides researchers with more control over variations in the luminous environments under investigation, reducing uncontrolled factors impacting the observer. Furthermore, many variations of the design space can be created and tested in VR, a task that is not easily feasible to complete in the real world. It is more convenient to use visualizations for randomized conditions. Although photographs and renderings have also been shown to be promising media for lighting research (Cauwert, 2013; Mahdavi & Eissa, 2002; Newsham, Cetegen, Veitch, & Whitehead, 2010) participants are not immersed in them, and the experience might not align well with that of a real space (Aries et al., 2010; Cauwert, 2013; de Kort, Ijsselsteijn, Kooijman, & Schuurmans, 2003).

VR can be used to enhance the realism of scenes. Moscoso et al. illustrated the use of stereoscopic images as an alternative way to represent real environments to evaluate the effect of daylight on perceived aesthetics (Moscoso, Matusiak, Svensson, & Orleanski, 2015). Later, Chamilothori et al. used stereoscopic images and tested the accuracy of immersive VR for the perception of daylight spaces by comparing the responses of participants in a real environment and its equivalent representation in a VR environment. In their experimental study, a total of 29 participants were interviewed in both VR and a real environment. Five aspects of subjective impressions related to daylit environments were measured: "perceived pleasantness", "interest", "excitement", "complexity", and "satisfaction with the amount of view" to the outdoor environment. The results showed a high level of agreement between the two environments, suggesting that an immersive VR environment can be a promising surrogate for lighting studies (Chamilothori, Wienold, & Andersen, 2018). Similarly, Kuliga et al. investigated the use of VR as a research tool to compare the experience of a real conference center with an analogous, highly detailed virtual model. The authors concluded that VR can be used as an empirical research tool in psychological and architectural research studies (Kuliga et al., 2015).

Rockcastle et al. used VR headsets to examine the relationship between design of architectural spaces and users' emotional responses. Subjective evaluations of simulated daylight architectural environments were collected and were compared to image-based measures related to impressions of visual interest. The authors concluded that impressions of "pleasant", "interest" and "excitement" can be predicted in immersive scenes (Rockcastle, Chamilothori, & Andersen, 2017).

A similar study using an immersive VR headset showed that facade geometry and daylight patterns can impact the emotional responses of participants in the space (Chamilothori, Chinazzo, et al., 2018). The authors examined the relationship between facade patterns and emotional responses through subjective assessments, as well as by measuring participants' heart rate and skin conductance. Three different facade variations were used to alter the perception of the participants: irregular pattern, regular pattern, and simple venetian blinds. The results indicated a strong effect of facade pattern design and daylight distribution on participants' visual impression as well as their mean heart rate—the authors noted that participants' mean heart rate was lower when exposed to the facade with an irregular pattern.

Although VR headsets have been shown to be adequate surrogates in lighting research (Hall et al., 2012), they cannot display high dynamic range images, as they have a limited luminance range. This shortcoming is problematic in studies that investigate visual discomfort associated with glare. Another limiting factor in using stereoscopic images is that although they provide a 360° view of the scene, participants are unable to freely walk around and view the virtual environment from different positions and angles within the room.

## 2.3 A New Perspective: The gap in photometric measurement and subjective impressions in lighting research

Lighting is an architectural element that reveals forms, enhances colors and textures, and thus our experience of a space. Louis Kahn once wrote: "A room is not a room without natural light"

("Louis Kahn: The Making of a Room," n.d.). We not only need to know how much light is available for people to see their surroundings, we also need to understand how they experience and evaluate their environment.

Since 1928, the most widely used metric for assessing daylight has been the average illuminance levels measured on the horizontal working plane. Although this method is sufficient for evaluating and confirming that the amount of light required for a specific task is provided, it does not illustrate the lighting characteristics of the space or of a facade design. For example, two widely different facade designs could produce similar daylight autonomy but possess atmospheres that will be perceived very differently. A quality daylit space is not the product of more lighting; rather, it is a product of carefully designed lighting.

The available current metrics can be used to evaluate lighting quantity. However, even if the values simulated may seem sufficient, they may fall short in measuring how the spaces are experienced in the real world. Additionally, calculating only one aspect of natural light, such as its illuminance, will not produce a meaningful index of how a space is perceived, and if occupants would be satisfied with the brightness of the space. A recent research study highlighted the discrepancy between objective daylight measurements through the use of daylight simulation tools and metrics and subjective qualitative preference judgments (Omidfar, Niermann, & Groat, 2015). The study indicated the need to augment quantitative lighting analysis with qualitative analysis to achieve successful luminous environments.

In designing building facades and skins, one of the major problems with current metrics, such as DA or sDA, is that the values are not closely linked to the facade design, so it is hard for designers to assess which part of the design can be adjusted for better performance. High dynamic range renderings of the space could potentially be used to detect the problematic areas of the design, however, simulating hourly HDR renderings for the entire year (8760 hours/year) can be time consuming and inefficient. Similarly, the use of a Bidirectional Scattering Distribution Function (BSDF)—which describes the amount, direction and the overall interaction of light with a component—can be challenging, as it requires an advanced understanding of lighting and that the codes required for lighting simulations be manually written (McNeil, 2014). Therefore, a central objective of this dissertation is the development of a better technique for measuring daylight entering though a building's facade, a technique that would provide a seamless connection between simulated light values and facade design.

As Lam has discussed, users do not base their judgment of the space on the actual luminance levels; instead, their judgment is based on how bright or dark the space appears and whether the environment meets their expectations (Lam, 1992). In regard to daylight quality and satisfaction, what is clear is that people prefer daylight over artificial lighting. The effect of light on an occupant's mood, behavior and satisfaction is also agreed upon among researchers. What has not been fully investigated is the possibility that our perception and satisfaction of daylight is affected by other perceptual attributes of our environment.

In surveying sixty subjects on their subjective preference for daylight, Cheung and Chung reported that out of seven influential attributes related to daylight performance ("general brightness", "desktop brightness", "perceived glare", "sunlight penetration", "quality of view", "user friendliness of shading control" and "impact of energy"), "quality of view" and "general brightness" were rated the most important attributes when evaluating daylight environments (Cheung & Chung, 2008). "Quality of view" was the highest-rated attribute in term of its importance to daylight performance. This result is intriguing, as "view quality" has no direct relationship to daylight availability in the space. This suggests that peoples' perception of daylight could be affected by other perceptual attributes of the environment, such as sun pattern, quality of view, or the amount of view of the conditions outside. Research on daylighting and facade geometry on satisfaction and perceptual evaluations is very limited. Thus, another central objective of this dissertation was to investigate what aspects of daylight people desire in their work environment and if their perception and satisfaction with brightness is influenced by other perceptual attributes in the space.

A total of four research experiments are discussed in the following chapters with the aim of elucidating the major objectives of this dissertation. The first study proposes moving beyond the common horizontal plane measurements and illustrates a technique to measure light spatially so that the simulated values can be linked to the facade design for further adjustments and improved performance. The second study discusses a new survey method to gain insight into the questions of daylight quality and users' expectations and preferences. The outcome of this section will provide designers a list of daylight attributes that can be used during facade design. It also highlights the importance of facade design (its size, geometrical patterns, materiality, and light transmission capacity) on the quality and distribution of interior lighting and its impact on users' subjective impressions. The third section illustrates an experimental study to deepen our understanding of the effect of simulation choices such as materials and presence of furniture, which could influence lighting studies on impressions and behavior. The final experimental study illustrates that satisfaction with lighting and brightness is affected by factors other than light levels. In this experimental study, facade design was the main driver significantly influencing participant's perception of the immersive scenes.

An important take-away from the review of the literature provided in this chapter is that facade design not only alters a building's energy performance and demands, it greatly alters the ingress and distribution of daylight and occupants' perception of and satisfaction with the environment. Thus, it requires special attention to maintain the desired outcome, i.e. contributing to the wellbeing of the end users and the overall building performance.

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# Chapter 3
# **Overview**

The previous chapter provided a review of the state of the art in designing building facades and skins. As discussed there, the effect of the geometrical design of a building skin on daylight quality and spatial daylight distribution remains overlooked, despite the development of simulation tools and advanced research on facade performance. Key findings indicate that there is a gap between skin design and the results of daylight simulation, as well as an in-depth understanding of occupants' satisfaction with brightness. Considering the contextual constraints of designing a high-performance building facade—skin design selection, analysis, optimization, time considerations—the challenges of creating a holistic and high-performance facade design effectively and efficiently have a substantial influence on architectural practice.

In this chapter, the methods used to evaluate the performance of skins and investigate the relationship between quantitative daylight simulation and subjective daylight impressions is explained. To do this, the chapter is divided into five subsections to explain the different methods used to address the multi-faceted research question of this dissertation. It is important to note that this chapter does not explain the methods used in each of the experimental studies in detail; rather, it is intended to illustrate the overall methodology used and justify its selection.

Structurally, this chapter consists of two thematic sections—quantitative and qualitative assessment of daylight—with relevant subsections. In the first section, the methods used to quantitatively assess daylight is discussed, focusing on the measurement of spatial luminance distribution to better understand the behavior of a building's skin. Next, the methods used to analyze the qualitative and perceptual attributes related to daylight is illustrated. For each method used, a brief discussion justifying its use and describing its possible limitations is provided. Finally, a summary of this chapter and a brief overview of the focus of the subsequent chapter is provided.

## 3.1 Quantitative Assessment of Daylight

The quantity of daylight in buildings, particularly office buildings, must be evaluated to provide the information necessary to understand whether occupants have the amount of light required to perform tasks. As discussed in the previous chapters, the calculation of illuminance levels in a particular space is often done on a horizontal plane roughly at the desk level, 2.5 ft above the floor line. The shortfall of this technique is two-fold.

First, the illuminance values generated from simulation on the horizontal plane illustrates the amount of light that falls on each sensor but is not directly linked to the areas of the facade that allow the light infiltration. For example, Figure 3.1 illustrates the result of simulation of the daylight autonomy of an office space with an ornamental building skin. From this analysis, we can understand where the space might have too much or not enough light, but it is difficult to fully understand how the skin design can be adjusted to improve the daylight performance of the design.

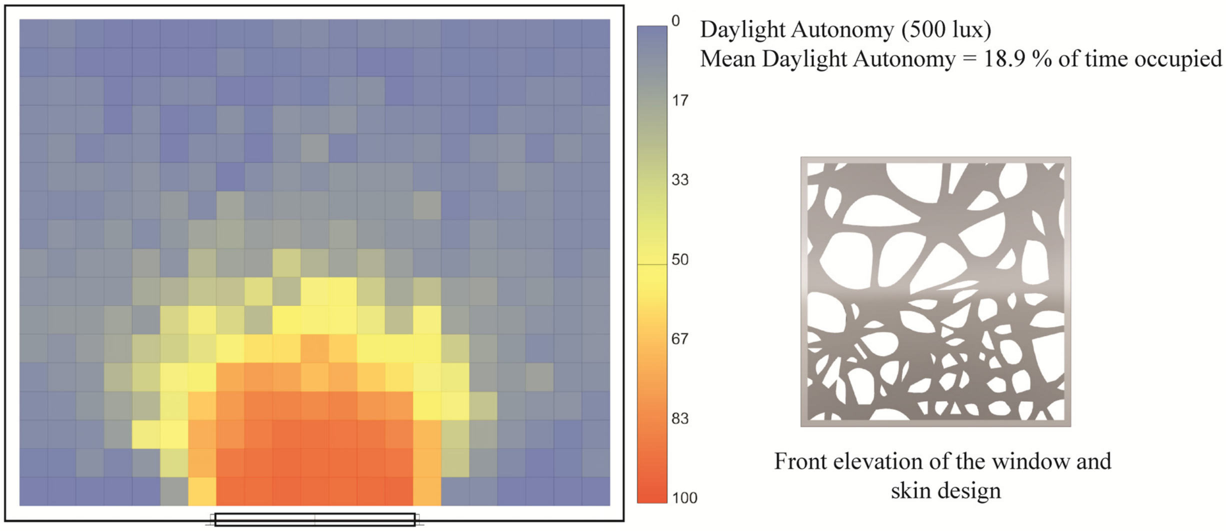


*Figure 3.1: Daylight Autonomy of a 'typical' office space with ornamental skin pattern*

Without a direct relationship between the light that passes through the building skin and the exact areas of the skin design that are allowing light infiltration, it becomes difficult to understand the full behavior of the design and adjust the areas of the skin design that must be further evaluated for improved performance. Second, the two-dimensional illuminance results do not fully characterize an interior space three-dimensionally or spatially. To evaluate the space three-dimensionally, practitioners, researchers, or designers generate high dynamic range (HDR) images of the space to measure the luminance values and understand the full behavior of the facade. However, generating HDR scenes for the entire year is challenging, time-consuming and can be computationally expensive. Additionally, the information generated may not be suitable to predict occupants' satisfaction with access to daylight. To fill the gap, this work proposes a technique to measure illuminance and luminance distribution through skin design. This technique is called Facade Photometry, a term coined by the author. It uses hemispherically distributed sensors to measure light distribution in the room. Data generated by this technique can be used to further adjust the design of the skin's geometry for improved performance.

### 3.1.1 Facade Photometry

**<u>Research Question:</u>**

How do we measure the effect of a building skin design on light distribution within the building, so the simulated data can be used to inform the design for better performance?

A building skin's geometry influences the infiltration, directionality, distribution and intensity of daylight. To categorize and fully understand the behavior of the facade as it relates to daylight transmission, its light distribution capabilities must be evaluated. Additionally, to design efficient facades that control natural light, there is a need for detailed knowledge of the skin’s behavior, the ways in which the skin’s geometry and surfaces affect light infiltration and distribution.

I. Procedure:

This section of the dissertation illustrates how light infiltrating through a building skin can be measured three-dimensionally, and how the data from simulation results can be used to further inform design. The Rhinoceros modeling tool and the Grasshopper plug-in are used to create three-dimensional environments; digital measurement meters and the Diva-for-Rhino simulation tool are used for daylight analysis.

II. Case Study:

A typical office space with a large window was created as a base case. To examine the effect of skin design on light intensity and distribution, six variations of the office space were evaluated. Each variation had a different skin, ranging from simple horizontal louvers to a complex pattern with an irregular design. The patterns are based on existing buildings but were modified to each have the same perforation ratio of 40%. The 40% perforation ratio was selected as it has been shown to be one of the most preferred solid-to-void ratios in previous studies on aesthetic preference (Chamilothori, 2019; Friedenberg & Liby, 2016) and with the intention of controlling the overall brightness of the scenes.

III. Digital Meter:

To fully understand the performance of each skin, the incident and emerging direction of light should be considered. Facade Photometry, the technique used to evaluate spatial light infiltration through the facade geometry, utilizes a bi-directional daylight modeling technique to measure light levels at each daylight sensor.

To determine the directionality of the light transmission though the skin's geometry, a hemispherical surface was modeled and placed in the center of the room facing the skin. The hemisphere was discretized in small patches with equal areas, in a manner similar to the Tregenza sky subdivision model (McNeil, 2013; Tregenza, 1987). Each patch was used for the placement of the daylight sensors. The sensors were placed on the concave face of the hemispherical surface following the normal vectors of the subdivided patches. Each sensor, therefore, possesses a XYZ coordinate location and viewing direction. A cylindrical meter was then placed around each sensor to control its field of view (FOV). Control of the FOV is required for two reasons: first, the illuminance data can be easily converted to luminance values if the sensor's FOV is known; and second, to limit the surface area seen by each sensor so we can precisely isolate the area of the skin that is allowing too much light infiltration to the interior space.

The size of the subdivision and the number of sensors was contingent on the aim of the research. In this study, 145 sensors with a 67-degree FOV were used to match the scene in Oculus VR headset. A more narrow FOV would be preferable if the aim is to link the simulated data to the skin geometry to adjust for improved daylight performance.

IV. Data:

The simulation produced hourly data on light infiltration through the skin geometry over the entire year. The data generated using this method resulted in a full spatial luminance distribution, i.e., the directionality, intensity, minimum, average and maximum peak values of daylight infiltration as a result of the skin's geometry. Once the simulation was completed, the data generated were traced back to the skin design and used to identify the areas of the skin where light infiltration was above or below the set thresholds (e.g. values that are <100 lux or >2000 lux). The data can also be filtered to highlight the areas of the design where too much light is infiltrating through the skin design for more than a certain percentage of the year.

V. Justification:

The use of a hemisphere rather than sensors on a plane allows for spatial measurement of daylight infiltration through the building skin. Because the sensors follow the normal of each patch of the hemisphere, their directionality and position is known. This will allow the simulation data to be linked to features of the design and to identify areas of the design that can be optimized for improved daylighting performance. This is an efficient and accurate simulation technique which also produces hourly illuminance data for the entire year; these data can easily be converted to a measure of luminance distribution through the skin’s design.

VI. Limitations:

Although the bi-directional modeling technique provides valuable information to fully understand the behavior of the facade's geometrical design at a specific position, one of the current limitations of this technique is that data from the sensors cannot be averaged to one value in a manner similar to Daylight Autonomy or other lighting metrics in which average values are used. The areas covered from the FOV of each sensor might overlap, resulting in overestimation of the average. If the FOV of the sensors were reduced to cover a smaller area to avoid overlaps, then many areas of the facade would be overlooked, resulting in underestimation of light levels.

The detailed process, including modeling of the three-dimensional building and the hemisphere, as well as the full explanation of the spatial distribution of daylight simulation, will be discussed in the experimental section of Chapter Four (Section 4-1).

## 3.2 Qualitative Analysis of Daylight

We perceive our environment three-dimensionally, observing and identifying all its elements. We characterize light as a three-dimensional phenomenon, one that shapes and alters our perspective and perceptions of our surroundings. Many prominent architects, such as Louis Kahn, Le Corbusier and Toyo Ito, have relied heavily on composing with light in a manner which highlights the materiality of a building, as well as juxtaposing different volumes; they have curated light in ways that would enhance the interior's spatial quality. It was clear to them that the need to bring light into interior spaces arises from more than merely complying with codes and standards or to facilitate the completion of specific tasks.

The ephemeral qualities of daylight, its brightness, contrast, spectral qualities, lightness, complexities, dynamics, and variability are what separates daylight from electrical lighting. These are the characteristics of daylight that influence our perception and are desired in architectural spaces. These characteristics of daylight are, however, inherently subjective and difficult to evaluate, which is why our knowledge of how they influence our perception is extremely limited. However, without understanding how facade designs affect daylight distribution and thus occupants' perceptions, we cannot fully understand the behavior of a facade and improve its performance. Therefore, in the next subsections, the methods used to evaluate the qualitative properties of daylight is laid out and their importance in influencing the perception and satisfaction of occupants is discussed.

First, the use of Conceptual Content Cognitive Mapping (3CM) to discover what aspects of daylight are important to people in office environments is discussed. The 3CM method provided the concepts users find relevant to the study of daylight and generate a list of relevant keywords to assess the quality of daylight in interior office spaces. Second, the impact of simulation choices, such as color and level of details associated with furnishings, on participant's subjective impressions in immersive scenes is illustrated. And finally, the use of immersive virtual reality as an effective tool to evaluate the impact of facade design and simulation choices on occupants' satisfaction with brightness is presented.

### 3.2.1 The Use of Conceptual Content Cognitive Mapping (3CM) for Studying Daylight in Office Environments

**Research Question:**

What is it about daylight that people like in their office environment? What should the overall appearance of an office space be? What are people's expectations and understanding of daylight, its size, color, geometry? What are the key concepts that people associate with daylight?

To answer these research questions, the Conceptual Content Cognitive Mapping (3CM) method, a survey technique widely used in Environmental Psychology research experiments was used.

This is a quantitative and qualitative research method for understanding the hierarchical knowledge structure of an individual's mental model (A. R Kearney & Kaplan, 1997).

I. Stimuli:

3CM is a unique technique which accesses and highlights what participants have experienced prior to the survey rather than what they physically see (Anne R Kearney, 2015). Thus, it eliminates the use of images or other visual stimuli, relying instead on conceptual content and participants' mental models.

In this survey study, participants were first given a series of prompts about the topic of the study to allow them to activate their mental model. Once the participants were ready, a series of questions relevant to the topic at hand were posed.

II. Questionnaire:

The aim of this section of the research was to create a list of key concepts that people associate with daylight in office environments. Therefore, the prompts and the questions posed were specifically focused on daylight in office settings. Specifically, participants were asked to generate and or select keywords that they considered important and relevant to the aspects of daylight in office environments they like, and that are important to them.

III. Participants and Procedure:

Typically, in the 3CM process the interviewer provides a list of concepts that participants can choose from in describing their ideas; however, in this experimental study it was decided to divide the process into two phases. The first was an open-ended process; after reading the series of prompts and questions, the participants were asked to generate a list of concepts relevant to what they like/dislike about daylight in office environments. The second phase followed the standard, structured method, in which the list generated in the first phase was given to the participants to select concepts from. In the open-ended pilot study, 15 subjects participated, generating 65 concepts. In the second, structured phase, a total of 50 subjects participated. All participants were unpaid volunteers recruited in person or by email.

In the second, non-pilot phase, the interviewer read a series of prompts and questions; when the participants were ready, they were given the list of daylight concepts and were asked to pick any keywords that they would use explaining their ideas about daylight in an office environment. They were asked to write each concept on a piece of card. When they had written all of the selected concepts that they found relevant to daylight, they were asked to group the cards into different categories, label each group, and rank them in order of preference. No restrictions were placed on the number of concepts chosen or on the number of groups.

IV. Data Analysis:

The data gathered from the survey study was processed using descriptive statistics and exploratory factor analysis (using "Factanal" in R software (Team, 2018) ) to highlight the similarities between concepts, the clustering of various groups and their rankings.

V. Justification:

The 3CM method was used in this experimental study as it provides an illustration of the way a person thinks about daylight in office environments. It is relatively easy to administer this type of survey and it is an effective method (Anne R Kearney, 2015) to create a picture of the larger problem, appropriate as a starting point for developing a framework to address issues related to daylight quality.

The survey process was divided into two sections, a pilot open-ended study and a semi-structured interview. As previously mentioned, in the pilot study, the participants were not given a list of concepts, and were instead asked to generate concepts they found relevant to daylight. The reasoning behind this decision was to ensure that the list provided in the second phase would offer a comprehensive list of concepts used by most people, avoiding limiting the concepts provided to terminology used only by the lighting research community.

VI. Limitations:

Because participants were asked to choose concepts and write each on a separate card, it became difficult to store and transfer all data from the cards to a digital format for analysis. Therefore, this method can be time-consuming and challenging to employ with a large sample size. Although the sample size of 50 people was adequate for this study, a larger sample size will be desirable to detect smaller effects. Additionally, the outcome cannot be generalized without further investigation.

### 3.2.2 The impact of color and simulation detail on subjective impressions of rendered scenes in immersive virtual reality

**Research Question**:

Do simulation choices such as color, texture and level of detail influence participants' subjective impressions of a scene?

Our knowledge of the impact of simulation choices, such as the presence of color, texture, and level of detail in a scene, on people's perceptions and subjective impression is limited. This study examined issues around simulation choices related to color and furnishing in the context of virtual reality; in doing so, it provided a much-needed detailed reference for VR, a rapidly growing field.

I. Stimuli:

In this experimental study, six variations of a typical office environment with a large window were created as visual stimuli. In each office variation, a different skin design was applied to the exterior of the facade. Although the design of the skin design ranged from simple horizontal louvers to complex irregular patterns, they were all modified to have the same opening ratio of 40% to maintain a constant level of brightness across all variations. To understand the effect of color and level of detail associated with furnishing, each office variation was rendered in three levels of color (fully colored, partly colored and grayscale) and two levels of detail (with and without furniture). The final 360-degree HDR images were shown to participants using the Oculus VR headset.

VII. Questionnaire:

Ten verbal questions related to participants' perception of the environment, such as how pleasant, exciting, interesting, and calming the space was perceived to be, as well as the visual complexity of the environment, and participants' satisfaction with the amount of view, ambiance, connection to outside, openness, and the brightness of each scene were composed for this study. At the end of each scene, the participants also responded to an open-ended question regarding what they liked/disliked in the environment.

VIII. Equipment:

A 360-degree stereoscopic scene of each office space was rendered in Radiance and projected in an immersive virtual reality platform, Oculus Go. Oculus Go is a standalone headset which, unlike other VR headsets, does not require extensive setup. It was chosen for use in this experimental study due to its compactness and portability.

IX. Participants and Procedure:

A total of 100 randomly selected subjects participated in the experimental study by wearing the Oculus Go headset and responding to the questionnaire. Each participant experienced a total of six randomly selected scenes. The participants were unpaid volunteers recruited by email or in person. The researcher interviewed each participant individually in a session that lasted no more than 20 minutes. The independent variables in the study were the skin variations, colored materials and level of detail, while the dependent variables were the responses to the questionnaire.

X. Data Analysis:

The dataset gathered was analyzed by using a linear mixed effects model, and highlighted the effect of both color and furniture on participants' subjective impressions. Statistical analysis of the data was conducted using R statistical software (Team, 2018) and the lmerTest R package was used to examine the effect of color and furniture on each attribute using linear mixed model analyses (Kuznetsova, Brockhoff, & Christensen, 2017). A Bonferroni-corrected significance level of .05/14=.0035 was used to account for the multiple comparisons used in this study.

XI. Justification:

During the design of virtual scenes using various rendering engines such as Radiance, one has the option of using default materials provided by the software or to create custom materials. The latter may be difficult and time consuming. Similarly, decisions must be made regarding whether to omit furniture in the model, as creating detailed furniture and custom geometries can also be time-consuming and computationally expensive—scenes with furniture will require additional simulation time for rendering.

However, knowledge about the influence of colored materials and furniture on participants' subjective impression in lighting studies, particularly in immersive environments is limited. Thus, to understand the effect of simulation choices, such as the use of colored materials and level of detail associated with furniture on participants' subjective impressions, it was imperative to conduct an experimental study in which different scenes could be presented to a large number of subjects. The goal was to observe how their ratings could change based on the characteristics of each scene.

The use of immersive virtual reality has been shown to be an adequate surrogate for experiments investigating lighting perception in real spaces (Cauwert, 2013; Chamilothori, Wienold, & Andersen, 2018; Hall, Navvab, Maslowski, & Petty, 2012). The virtual reality headset was an effective tool in this experimental study, as it allowed the participants to be fully immersed in the scene and provided a detailed and consistent representation of the space.

## XII. Limitations:

However, as previously mentioned, the scenes in this experimental study were pre-rendered and projected in Oculus Go; therefore, participants were not able to move around within the immersive scenes. This was one of the limitations of the study, as participants were not able to view the environment from different locations of the room or move closer to the facade. Other limitations of using VR headset include limited depth perception and feeling of presence.

### 3.2.3 Subjective impressions of a space influence brightness satisfaction: an experimental study in virtual reality

**Research Question:**

Could occupants' satisfaction with brightness be affected by perceptual attributes of their environment other than light intensity?

Considerable research has been devoted to identifying measured light levels of interior environments to predict occupants' impressions of brightness, and the influence of physical properties of lighting, such as light uniformity, on the perceived brightness of a space (Flynn, Spencer, Martyniuk, & Hendrick, 1973; Hawkes, Loe, & Rowlands, 1979; Loe, Mansfield, & Rowlands, 1994; Mahdavi & Eissa, 2002; Rea, Mou, & Bullough, 2016; Stokkermans, Vogels, de Kort, & Heynderickx, 2017; Veitch & Newsham, 2000). Brightness satisfaction, however, is a unique indicator that encompasses satisfaction not only with light levels but also with the quality and distribution of light.

If occupants' satisfaction with brightness is affected by other perceptual attributes associated with the overall design of the environment, such a finding would highlight the influence of design on sustainability and energy savings. The same level of satisfaction with brightness could then be achieved at lower illuminance levels by altering the design of the environment. Therefore, in the last section of the dissertation research, a subjective experimental study was conducted in immersive virtual reality to investigate the influence of perceptual attributes such as perceived pleasantness, or satisfaction with the amount of view, on occupants' satisfaction with brightness. Additionally, the presence of color and level of detail associated with furnishing was varied between scenes to investigate the influence of these simulation factors on participants' satisfaction with brightness in immersive scenes.

I. Stimuli:

In this experiment, six variations of a typical office environments with a large window on the south facade were created as visual stimuli. A different skin design was applied to the exterior of each office variation. The skin designs were based on existing buildings, ranging from simple horizontal louvers to complex irregular patterns. However, to maintain a constant level of brightness across all variations, the geometry of each pattern was modified so each possessed the same opening perforation ratio of 40%. The scenes were created using three levels of colored scenes (fully colored, partly colored, and grayscale) and two levels of detail (with and without furniture). The scenes were rendered using a method which combines physically based renderings from Radiance projected a in virtual reality headset for an immersive experience. This technique is a promising surrogate (Hall et al., 2012) for real daylight spaces in experiments investigating occupant perception of daylit environments. The six skin variations, along with three colored rendering variations and two levels of detail, resulted in a total of 30 immersive scenes.

II. Questionnaire:

Ten verbal questions related to participants' perception of the environment, such as how pleasant, exciting, interesting, and calming the space was perceived to be, as well as the visual complexity of the environment and participants' satisfaction with the amount of view, ambiance, connection to outside, openness, and the brightness of each scene were composed for the study. At the end of each scene, the participants also responded to an open-ended question regarding what they liked/disliked in the environment.

III. Equipment:

See Equipment in Section 3.2.2 IX.

IV. Participants and Procedure:

A total of 100 randomly selected subjects participated in this experimental study by wearing the Oculus Go headset and responding to the questionnaire. Each participant experienced a total of six randomly selected immersive scenes. The participants were unpaid volunteer recruited by email or in person. The researcher interviewed each participant individually in a session that lasted no more than 20 minutes. The independent variables in the study were the skin design variations, colored materials and level of detail, while the dependent variables were the responses to the questionnaire.

V. Data Analysis:

The dataset gathered was analyzed quantitatively using a linear mixed effects model to highlight associations between the attributes. Model analyses was conducted in R (Team, 2018) using the R software package *lmerTest* (Kuznetsova et al., 2017). Additionally, the open-ended responses were analyzed qualitatively by decoding participants' responses to further understand their individual experiences in each scene.

VI. Justification:

To investigate the associations between the attributes and examine if participants' satisfaction with brightness is influenced by other perceptual attributes of the environment, it was imperative to conduct an experimental study in which different office environments with same brightness levels were presented to a large number of subjects. This would allow observation of how their satisfaction with brightness was influenced by characteristics of the scene. The virtual reality headset was an effective tool in this experimental study, as it allowed the participants to be fully immersed in the scene and provided an accurate representation of the space.

VII. Limitations:

However, since the scenes in this experimental study were pre-rendered and projected in Oculus Go, participants were not able to move around in the immersive scenes. This was one of the limitations of the study—participants were not able to view the environment from different locations of the room or move closer to the skin design. Additionally, similar to other digital displays, the Oculus Go headset is not capable of accurately producing the level and intensity of sunlight; however, because in this experimental study the brightness levels were maintained at the same level, it is my belief that this particular limitation did not influence the results. Other limitations of using a VR headset include limited depth perception and feeling of presence. A larger sample of spaces, subjects and sky conditions will be required to validate the generalizability of the results.

## 3.3 Summary

Creating architectural environments—in which people spend more than 90% of their lives (Brager, Zhang, & Arens, 2015; Evans & McCoy, 1998)—requires detailed knowledge of the effect of the design on both the physical properties of the environment, such as light levels, and on the people within it. This endeavor is inherently both quantitative and qualitative in nature. Therefore, the aim of these research studies was to conduct a comprehensive evaluation of the performance of skin design in regard to light infiltration, distribution, and its influence on occupants' subjective impressions.

The first section of this dissertation study introduces a novel method, Facade Photometry, which allows for spatial distribution measurements of light infiltrated through a building facade. This method uses a bi-directional technique by evaluating light levels on a hemisphere. Because the sensors on the hemisphere follow the normal of the surface, each has a specific coordinate location and viewing direction. This information allows the researcher to link the values of the sensors to the areas of the skin design that are responsible for the light infiltration. In doing so, the specific areas of the skin that allow light infiltration above or below the desired thresholds can be identified.

The second section of this chapter discusses various experimental studies that were conducted to gain insight into the questions related to the assessment of light quality as affected by building skin. Different methods were used in each experimental study. The goal of this section of the research was to use methods and techniques that could efficiently produce accurate results to answer the research inquiry of each research question.

The first experimental study uses 3CM to gain insight regarding what aspects of daylight people desire in office environments, highlighting their likes and dislikes. What was particularly interesting about this method is that instead of using images, it used people's mental models—their past experiences, rather than what they were shown in an image. Although visual stimuli are effective in survey studies, they could potentially bias the results depending on the type of images participants view. Therefore, it was decided to find a method for this study that did not rely on visual stimuli, resulting in the choice of 3CM.

The second and the third experimental studies described in this chapter illustrate the use of a virtual reality headset as a promising surrogate for investigating the effect of luminous environments on participants' perception and subjective impressions. The Oculus Go headset allowed the immersion of participants in six variations of an office space. Each variation had a different skin design, levels of color and were presented with or without furniture. The aim of these experimental studies was to understand the effect of simulation choices such as the use of color and furniture on participants' impressions of the scenes, and the associations between different perceptual attributes of the environment. Specifically, the last experimental study investigated how participants' satisfaction with daylight was influenced by other perceptual attributes of the simulated office environment.

Table 3.1 summarizes the four studies presented in the dissertation.

*Table 3.1: Brief summary of the four research studies.*

| **Chapter No.** | **Chapter 4** | | | |
|---|---|---|---|---|
| | **Section 1** | **Section 2** | **Section 3** | **Section 4** |
| **Purpose of the study** | analysis of spatial daylight distribution through building facades & creating a feedback loop to connect simulation values to the skin design | to identify the aspects of daylight that are important to occupants and to create a list of daylight lexicon for qualitative studies | to examine the impact of simulation choices on participants' subjective impressions | to assess the influence of skin design and daylight distribution on participants' brightness perception |
| **Methodology** | measuring daylight ingress on hemispherical sensor arrangement | open and structured 3CM | experimental study in VR | |
| **Participants No.** | NA | open-3CM= 15 participants structured-3CM= 50 participants | 100 | |
| **Analysis** | simulation-based study | statistical analyses using descriptive, & exploratory factor analysis | statistical analyses using descriptive, & linear mixed effects model | |

In Chapter Four, each experimental study is presented in detail. The discussion of each study starts with an introduction, highlighting a literature review and the challenges in the field, followed by a step-by-step description of the process and methods used, the results of the experiments, and lastly, discussion and suggestions for future directions.

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# Chapter 4
# Quantitative and Qualitative Evaluations of Facade Design
## Section 1- Facade Photometry


### Abstract

This section of the dissertation presents a novel technique to evaluate how building facades propagate light into interior spaces, and how simulated data can be used to inform design for better performance. Just as electric light photometry charts the luminous intensity around a light fixture, Facade Photometry, a term coined by the author for the method introduced in this work, uses annual simulations and localized weather data to create temporally based illuminance and luminance distributions. This photometric chart is a unique signature of a particular facade design measured at a specific geometric point in a specific orientation located in a particular climate. Facade Photometry is intended to provide designers the ability to more easily compare the performance of complex and intricate glazing and daylight control systems. By linking data from the daylight simulation to the facade design, the areas of the design that should be adjusted for improved performance are highlighted.

Current methods of obtaining annual luminance values require the collection of High Dynamic Range (HDR) images, which can be a time-consuming and computationally expensive task. The method proposed in this paper uses a bi-directional measurement of daylight received by digital sensors arranged hemispherically in a room and aimed at the facade. The data can be used to obtain hourly spatial illuminance and luminance distributions, as well as vertical eye illuminance distributions. While further analysis is necessary in order to fully understand the ways in which

the data collected can be used, this method has the potential to become a streamlined tool to further aid designers in the pursuit of designing highly energy efficient, high performance, and comfortable building facade.

### 4-1.1 Introduction

Since the first light survey in an interior space in 1865, we have progressed significantly in our understanding of "good" daylighting in buildings (Ashdown, 2014; Reinhart, F, Mardaljevic, & Rogers, 2013). Our metrics and simulation tools have, of course, evolved in parallel. The Daylight Factor (DF), initially introduced in 1895, was followed by the Lumen Method in 1928, an understanding of luminance distributions in 1942, and the Daylight Glare Index (DGI) in 1950. In 1989, Daylight Autonomy was introduced, Useful Daylight Illuminance (UDI) in 2005, and most recently, Spatial Daylight Autonomy (sDA) and Annual Solar Exposure (ASE) in 2012 (Hopkinson, 1963; Kota & Habrel, 2009; John Mardaljevic & Christoffersen, 2016; Nabil & Mardaljevic, 2006; Peterson, 2015).

Clearly, there has been a trajectory of achievement in evaluating and simulating natural light. However, most of these metrics, aside from glare studies, rely on measuring daylight quantity on a horizontal working plane approximately 2.5 ft (~0.76 m) above the floor at desk level. The most widely used metrics for assessing daylight have continued to rely on assessing the horizontal working plane, overlooking the notion that most occupants now conduct work on computers with vertical, illuminated screens.

Building facades, skins and shading systems can have a dramatic effect on the distribution, directionality and intensity of daylight entering a space, yet commonly used metrics have difficulty accounting for these effects. The simulation results generally illustrate whether the space conforms to the recommended standards and recommendations, and if there are over- or under-lit areas in the space, but offer no direct link between the data and the facade design. This limitation makes it very challenging for designers to understand how to improve their design without going through several iterations of designs that may or may not perform better than the original option.

In addition to these shortcomings, most current metrics overlook the inherent dynamic nature and variability of daylight through building facades (S. Rockcastle & Andersen, 2013). Measurements on a horizontal plane cannot possibly illustrate all the lighting characteristics of a facade design. For example, two wildly different facade designs could produce similar daylight autonomy distributions.

Therefore, in order to understand the behavior of daylight through different facade designs, a method that measures the transmission, intensity and distribution of light through the facade is necessary. Facade Photometry, a technique introduced and discussed in this work, can measure the illuminance distribution of light, and can further be used to link the simulated data to the skin design so that designers can identify the areas of the facade that can be adjusted for improved performance.

The aim of this research is threefold: first, to introduce a new technique which utilizes a network of sensors modeled on an imaginary hemispherical surface to measure the incoming light through the skin design. Second, take advantage of the controlled field of view (FOV) of the custom sensors to readily convert illuminance values to luminance values, thus eliminating the need for high dynamic range renderings for luminance measurements. Third, to illustrate a technique to directly link simulated data to the skin design, highlighting areas that are above (or below) a certain light threshold so the design can be adjusted for improved performance.

4-1.1.1 Limitations of Common Lighting Design Metrics

While available metrics and indices provide valuable information about a space, they all possess some limitations and inadequacies. For example, the most commonly used metric in lighting design is the Daylight Factor, which is defined as the percentage of outdoor illuminance, E, that falls on the indoor work plane (Hopkinson, 1963). Though this is a simple and sometimes useful metric to quickly evaluate illuminance values on a working plane, because it is calculated using a CIE overcast sky, it does not account for a specific climate, nor does it factor in the effect of direct sun exposure, orientation and potential glare (J. Mardaljevic, Heschong, & Lee, 2009). This is not to say that the DF is not useful and should not be utilized, but to emphasize the importance of understanding the information each metric provides and their shortcomings. If the goal is to quickly assess the potential amount of light in a space, then the DF can be useful. However, if the exact amount of daylight as it relates to the building orientation and climate is important, then other, annual climate-based metrics, such as sDA or UDI, should be considered, as they provide a more accurate assessment of horizontal illuminance.

Lighting metrics, when used in computer-based simulation approaches, can be broadly divided into two categories, each of which express unique luminous qualities: 1) illuminance and luminance and 2) point-in-time and annual calculations. Task-based metrics rely on illuminance levels on a horizontal plane, typically modeled at desk level, while visual comfort metrics, usually assessing glare, rely on luminance or luminance contrasts in the field of view. Luminance-based metrics can identify localized contrast in addition to average or background luminance values and overall brightness. Currently, the most widely used method to obtain luminance measurements is the rendering of HDR images of a particular view for a specific moment in time, followed by post-processing and analysis of the image to obtain luminance values. Rendering hourly HDR images for the 8760 hours of the year and analyzing/post-processing each image to obtain the luminance values is not efficient, economical or effective. In 2009, Wienold proposed a method based on Daylight Glare Probability (DGP) using illuminance values at the eye level as well as simplified HDR images for each hourly time-step. This method is also implemented in the draft of the European standard (prEN17037) "Daylight of buildings". Although this method uses a very efficient luminance-based evaluation method, the calculation this method requires for several viewpoints and viewing can be time-consuming (Wienold, 2009a).

Other methods, such as the Bidirectional Scattering Distribution Function (BSDF) (3-phase and 5-phase) discussed by Andy McNeil (Andy McNeil, 2014) have the capability to characterize light transmission, reflection and directional distribution of the facade. However, systems that are inhomogeneous in design cannot be easily studied using any BSDF, either measured or calculated using genBSDF. This is because the BSDFs assume that the distribution is constant across the surface of a complex fenestration system. While there are "tricks" to overcome this limitation, this particular constraint, formed part of the motivation for finding a new method in this research study.

As luminance is a key metric closely related to the way in which the human eye perceives brightness and contrast, luminance and vertical eye illuminance measurements become the key variables in assessing the performance of the facade and its effect on the environment it encloses relative to occupants' perceptions of daylight distribution. Previous research studies have also shown the correlation between vertical illuminance at eye level and glare perception (Wienold, 2009b). Thus, this study also illustrates how luminance distribution can be efficiently calculated using climate-based simulation metrics.

#### 4-1.1.2 Light Measurements: Challenges of Using Far-Field vs. Near-Field Photometry

In the field of photometry, light is measured in terms of its perceived brightness to the human eye, which is different than measuring radiant energy in terms of absolute power (Bass, 1995). Because photometry is a polar measurement of candela values, the luminous intensity of a light source is defined from all angles. There are various apparatuses, meters and techniques to physically measure the luminous flux and intensity of luminaires. For example, to assess the performance of a luminaire, engineers typically use either a far-field photometric measurement procedure or near-field measuring techniques. Far-field measurement requires the photometer to be at a distance roughly five times greater than the maximum projected dimension of the luminaire. In near-field photometry, the meter can be at a distance of roughly the maximum width of the luminaire (Ashdown, 1993). Employing photometric data from a large distance, i.e. one appropriate for far-field measurement, evaluates the fixture as a point source which is photometrically homogenous (Ngai, 1987). It can be argued that a building facade can be viewed as a light fixture, but one whose light source, the sun, is dynamic. Therefore, neither far-field nor near-field methods are appropriate for assessing the performance of a building facade system.

It is obvious that a building facade cannot be viewed either as a point source or as a homogenous structure, and since the sensors need to be at the observer position, the rule of far-field photometry cannot be utilized. On the other hand, a near-field approach allows us to calculate light intensity and distribution, considering the fixture as a collection of components with unique photometric behavior (Ngai, 1987). The difficulty with applying rules for near-field measurements in measuring facade performance is the location of the sensors in relation to the fixture. Because the facade is a large area source, having the sensors at a distance equal to the width of the fixture would require the sensors to be so far away they could not accurately capture the light distribution. It is also important to note here that neither method has ever been used to assess shading systems or building facades in general.

### 4-1.2 Method

A digital technique is required to measure light infiltration through the facade such that the data can then be used to inform the design of the facade. The different components of the method used to develop the measuring technique are described in the following sections.

#### 4-1.2.1 Software

This study required digital models and a validated daylight simulation engine. Detailed digital models of six office environments were created in the Rhinoceros (Rhino) CAD environment. Rhino is a stand-alone, commercial NURBS-based 3D modeling tool developed by Robert McNeel and Associates (McNeel, 2010).

Custom daylight sensors and aperture-type meters for the bi-directional measurement technique were developed in Grasshopper, a graphical algorithm plug-in for Rhino which allows for parametric modeling and scripting.

All daylight simulations were performed using the DIVA Grasshopper plug-in (Jakubiec & Reinhart, 2011) which supports a series of performance evaluations. The models were exported from DIVA Grasshopper into the validated Radiance simulation program. All hourly light distribution for each facade were simulated using the Facade Photometry method.

4-1.2.2 Case studies

A typical office space with one large window facing south was used in this study. The office measured 19.6 ft (6 m) wide, 16.4 ft (5 m) deep, and 9.8 ft (3 m) high. The glazing portion of the facade measured 6.5 ft(2 m) wide by 6.5 ft (2 m) high.

Six variations of building skins developed in previous studies (Chamilothori, Wienold, & Andersen, 2018) were used. The skin variations are based on existing buildings but were modified to have the same perforation ratio of 40 percent to control for brightness. Each skin variation ranged from simple horizontal louvers to complex geometrical patterns (Figure 4.1.1). To allow daylight simulations, all modeled surfaces were assigned materials with specific reflectances in DIVA. The RGB reflectance, specularity and roughness of the main materials are as follows: walls (0.7, 0.7, 0.7, 0, 0), floor (0.31, 0.31, 0.31, 0, 0), ceiling (0.8, 0.8, 0.8, 0, 0), building skin (0.25, 0.25, 0.25, 0, 0), double-pane clear glazing (visual transmittance = 80%, RGB transmissivity = 0.87, 0.87, 0.87). Figure 4.1.1 illustrates the selected building skin patterns, the software used to create the digital models and light analysis, and 360° HDR renderings of the interior spaces with different skin variations.

For the climate-based daylight simulation, the Geneva 067000 (IWEC) weather file and International Commission on Illumination (CIE) clear sky conditions were used. The radiance simulation parameters (Table 4.1.1) were selected to reduce simulation time while accurately representing the light distribution in each space.

*Table 4.1.1: Radiance simulation parameters*

| Ambient Bounce | Ambient Division | Ambient Sampling | Ambient Accuracy | Ambient Resolution |
|---|---|---|---|---|
| 4 | 1024 | 256 | 0.1 | 256 |

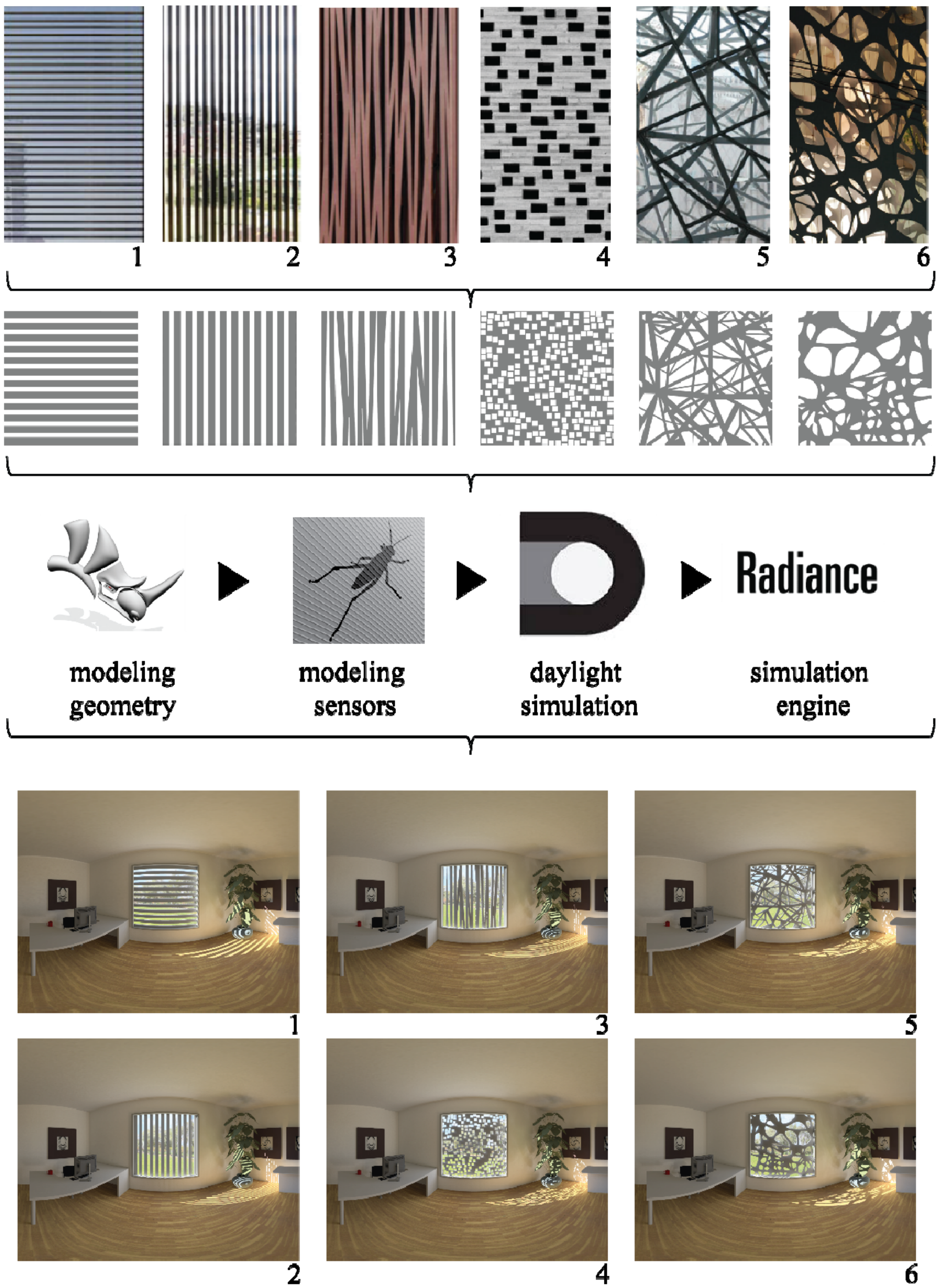


*Figure 4.1.1: The workflow diagram of the six case studies. The skins were based on those of existing buildings, shown on the top of the diagram. [1] Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012. [2] Freshwater House, Chenchow Little, Sydney, Australia, 2008. [3] Selcuk Ecza Headquarters, Tabanlıoglu Architects, Istanbul, Turkey, 2013. [4] Kew House, Piercy & Company, Richmond, United Kingdom, 2014. [5] Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002. [6] Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

4-1.2.3 Creating the digital sensors and aperture-type meters

Facade Photometry is a bi-directional technique which uses custom sensors modeled on the concave face of an imaginary hemispherical surface. The sensors face the window and follow the direction normal to the surface of the hemisphere. Each sensor possesses an XYZ coordinate location, viewing directions, and an angle that can be used to assess their FOV. Different discretization of the surface for sensor location and FOV can be used depending on the aim of the project and the complexity and intricacy of the building skin design. In this project, the hemisphere was divided into 145 patches, similar to the Tregenza sky model (Andrew McNeil, 2013), resulting in 145 sensors, each located in the center of individual patches, as illustrated in Figure 4.1.2.

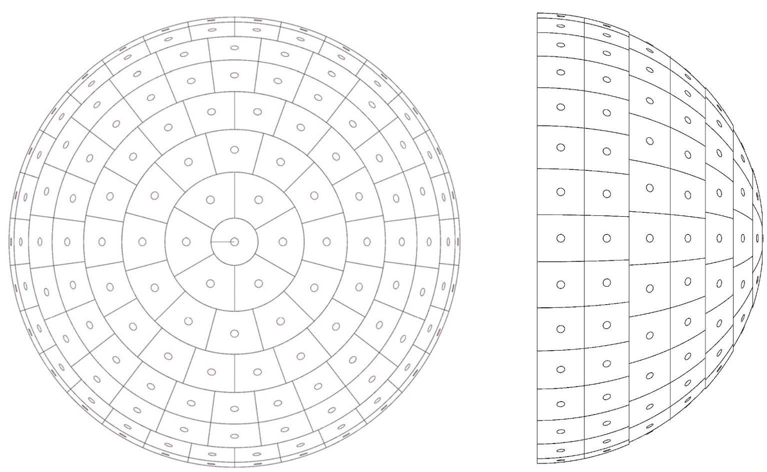

*Figure 4.1.2: From left to right- Front and side view of the imaginary hemispherical surface and the 145-sensor arrangement*

A physical measuring technique in near-field photometry using an aperture-type photometer has previously been developed. This type of meter measures the luminous flux contained within a specific solid angle and an area of a sensor (Ashdown, 1993). This research study uses the specification of the size of the meter and its projected FOV. An aperture-type meter geometry, i.e. a black cylindrical shield (as shown in Figure 4.1.3) was developed and used around each sensor to constrain its FOV. Following Ashdown's recommendation on the size of the aperture-type meter (Ashdown, 1993), a cylindrical shield measuring 0.35 ft (10 cm) in radius and 1.5 ft (45 cm) in length was used, providing a sensor FOV of 25°. This meter measures an approximation of luminance to its finite field of view. This technique calculates the luminance transmitted or reflected off various complex building skins at an equal solid angle as viewed from the interior space. The following equation is used to calculate the FOV of the sensors based on the size of the meter:

$$\text{FOV}(\theta) = 2 \times \tan^{-1}(\text{Radius} \div \text{Length}) \qquad \text{Eq. 1}$$

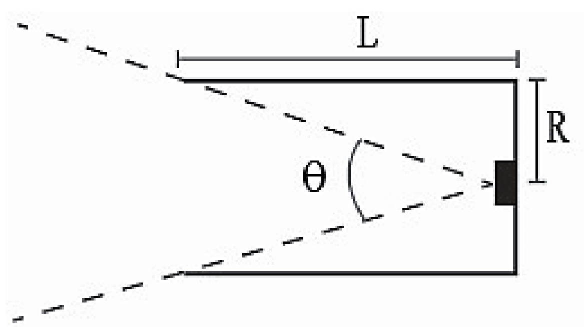


*Figure 4.1.3: Diagram of the aperture-type meter used to constrain the FOV of each sensor to 25°*

R= Radius

L= Length

The hemisphere is located in the room facing the glazing; thus, the sensors are in close proximity to the facade and each sensor views a portion of the interior space based on its FOV (Figure 4.1.4). Because the sensors follow the directions normal to the surface of the hemisphere, those closer to the edge of the hemispherical surface face the surrounding wall surfaces away from the facade. These sensors can detect the light levels reflecting from the walls, ceiling and floor of the interior environment.

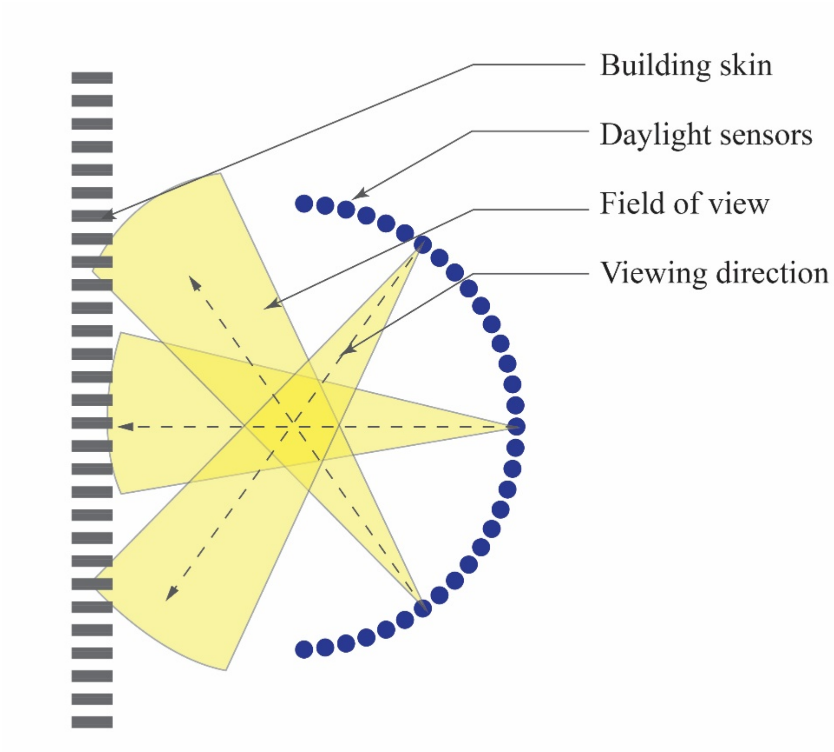


*Figure 4.1.4: Concept diagram of the sensors, viewing directions and FOV*

4-1.2.4 Illuminance to luminance calculations

Following the equations provided in the Illuminating Engineering Society (IES) handbook, luminance values can be calculated using the simulated illuminance values. Because aperture-type meters follow the normal of the hemisphere and the values are not measured horizontally, no corrections will be needed. Thus, the following equations can be used to calculate the luminance values of each sensor using the simulated annual illuminance simulation.

The calculation of the illuminance from a luminance distribution of a hemisphere is defined as:

$$E = \int L \times \cos\theta \times d\omega \qquad \text{Eq. 2}$$

For the aperture-type meter this equation can be simplified to:

$$E\ (\text{meter}) \approx L\ (\text{meter}) \times \Omega(\text{meter}) \qquad \text{Eq. 3}$$

Therefore, to calculate luminance:

$$L\ (\text{avg}) = \frac{E(\text{meter})}{\Omega\ (\text{meter})} \qquad \text{Eq. 4}$$

here $\theta$ is ½ of the angle of the cylindrical meter or the FOV.

Thus, to convert illuminance to luminance values using the sensors with FOV of 25°:

L=E/ (2π (1-cos (25 × π/360))

$$L = \frac{E}{2\pi\,(1 - \cos\,(25\ \times\ \pi/360))}$$

$$L = \frac{E}{0.148}$$

E = Illuminance

L = Luminance

$\theta$ = Angular distance from sensor normal to source (which is zero due to the viewing angle, so cos $\theta$ = 1)

Ω = Solid angle of the aperture-type meter

The aperture-type meter measures an approximation of luminance due to its finite field of view. Once the values are simulated using DIVA Grasshopper, they can be divided by the solid angle for average luminance, as shown above. The hemispherical sensor arrangement is equivalent to a fisheye lens with a 180-degree field of view, with each sensor having a FOV. In a sense, this setup results in a low-resolution fisheye image where each pixel has annual luminance values calculated.

### 4-1.3 Results

Once the annual climate-based simulation is completed, the results can be viewed in various ways depending on the scope and aim of the research. The data can be viewed on monthly bases, as shown in Figure 4.1.5. In this example, the data are organized so sensors that are reading less than 100 lux are highlighted in blue, those reading 100–2000 lux in yellow, and those above 2000 lux in magenta. Different thresholds can be used depending on the aim of the research.

In this project, sensors reading over 2000 lux or 13,513 cd/$m^2$ will be the focus, as these levels could lead to both visual discomfort associated with glare and overheating of the space. Figure 4.1.5 illustrates the sensors receiving over 2000 lux (13,513 cd/$m^2$) during the months of January, February, March, June, July, August and November.

In addition to viewing the measured data monthly, the values can be viewed per sensor, as shown in Figure 4.1.6. Viewing the data per sensor is an excellent way to see the dynamic of the daylight in the space as influenced by the skin design. Figure 4.1.6 illustrates the illuminance readings of four selected sensors over the entire year (8760 hours). Similarly, the hours in which the sensor reads over 2000 lux are highlighted in magenta.

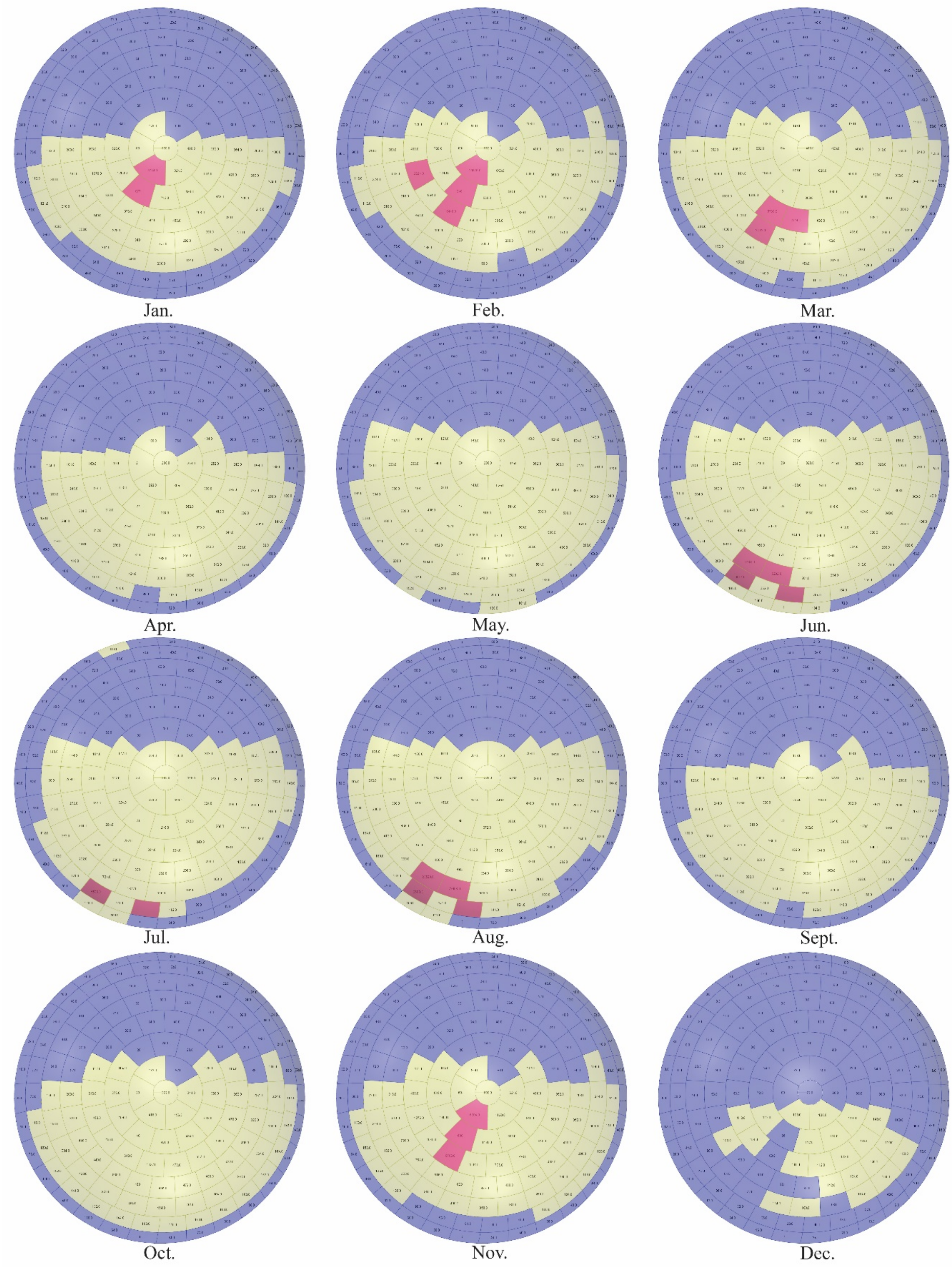


*Figure 4.1.5: False color of illuminance values at 12:00 pm at each sensor on the hemisphere using the Airspace skin design. Sensors receiving less than 100 lux are shown in blue, those between 100–2000 lux in yellow, and sensors reading above 2000 lux in magenta.*

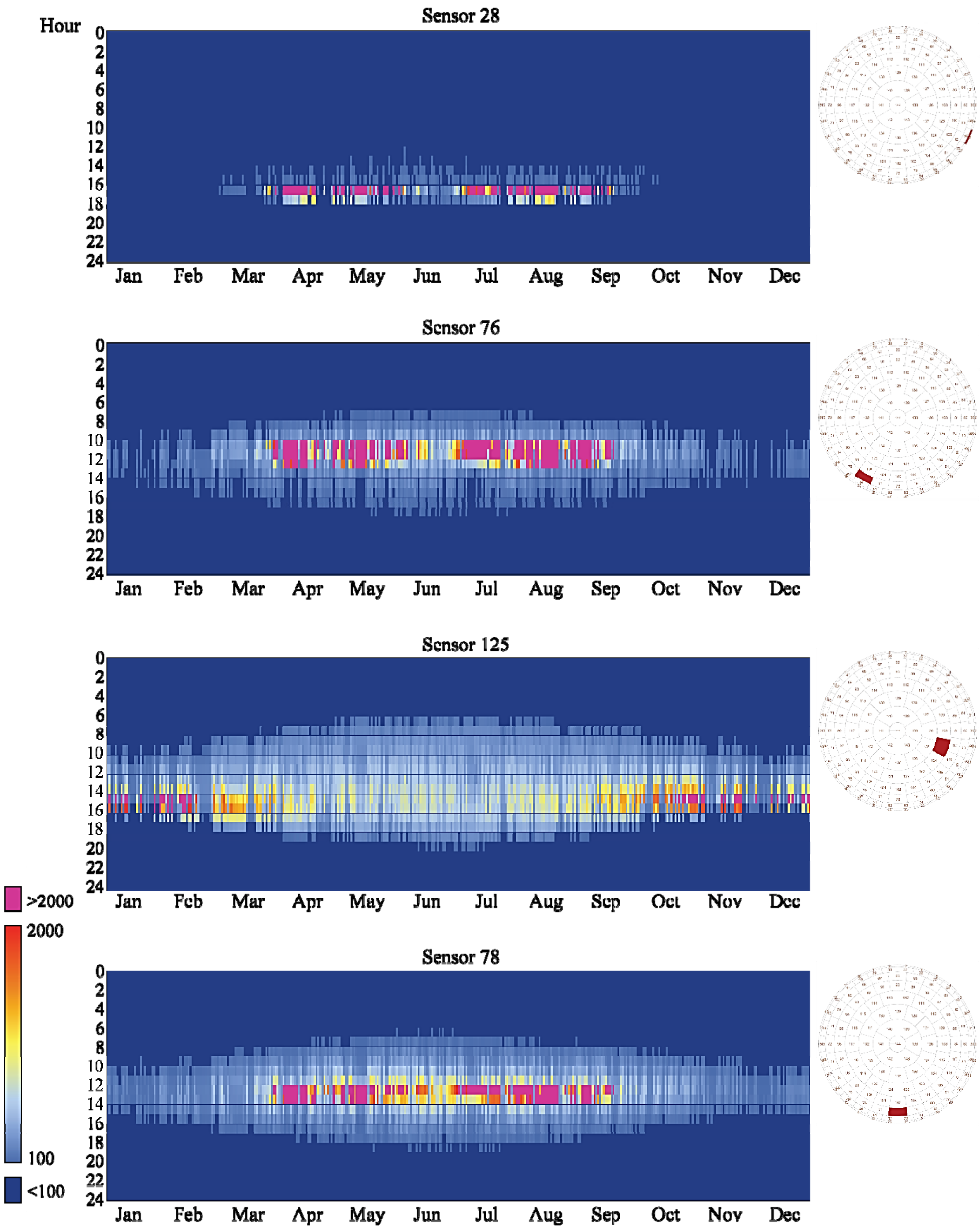


Figure *4.1.6: An example of visualizing annual (8760 h) illuminance values received at each sensor using the Airspace skin pattern. Each pixel of the image represents an hour of the year, with x-axis showing each month and y-axis showing the hours (24 h/day). The location of each sensor is highlighted on the hemisphere on the right.*

#### 4-1.3.1 Linking the measured data to the building skin design

Since the viewing direction and FOV of each sensor is defined, all sensors on the hemisphere can be linked to the building skin. So, if particular sensors are reading high or low illuminance values, they can be highlighted, traced back to a particular region of the building skin, and adjustments can be made to the geometry of that area. Figure 4.1.7 demonstrates the link between data from the daylight simulation and the building skin design, highlighting the areas of the skin that allow interior illuminance >2000 lux over the entire year. The data are further filtered to show the areas of the building skin that allow illumination over a certain threshold, such as 2000 lux for more than 2% of the year. The thresholds can be defined based on the scope of the project. Typically, a 5% threshold is used in glare analysis; the minimum recommendation for glare protection is that the Daylight Glare Probability (DGP) for the space does not exceed a value of 0.45 in more than 5% of occupied hours (Deroisy B & Deneyer A, 2017; Wienold, 2009b). In this research, a 2% threshold (175.2 h) was selected, as none of the sensors in this particular design read 2000 lux for more than 5% of the year.

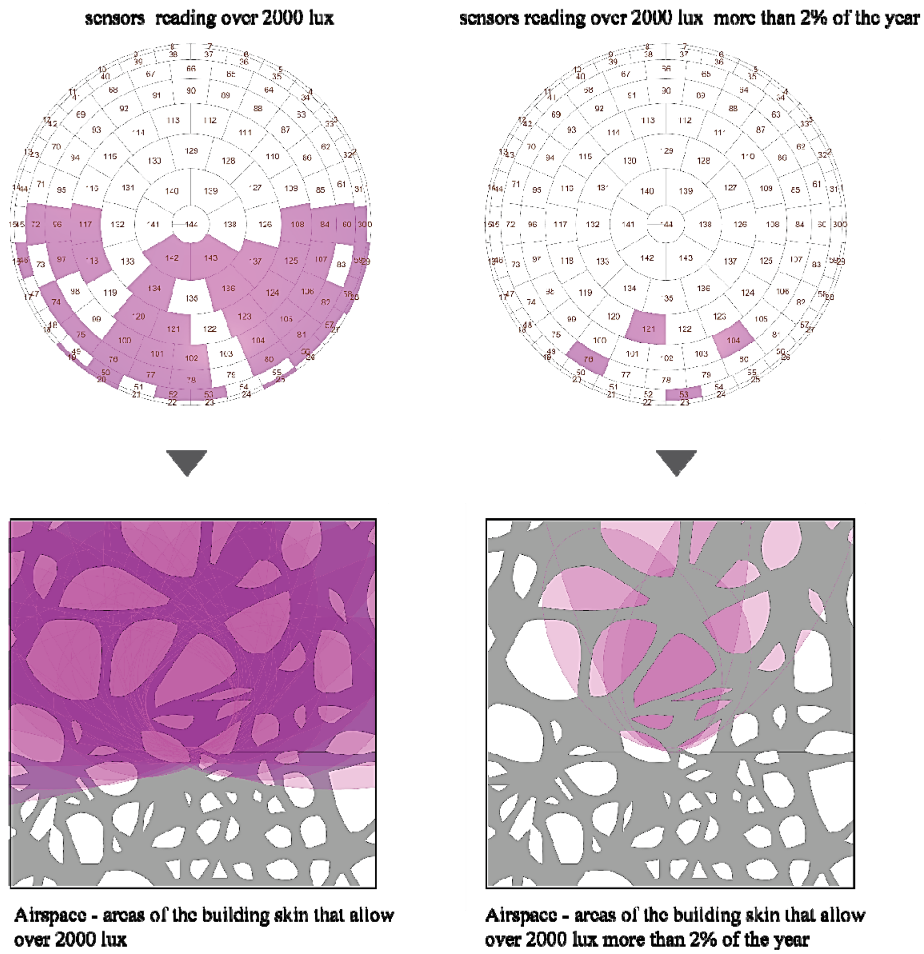


*Figure 4.1.7: Sensors reading (left) over 2000 lux over the entire year (right) over 2000 lux for more than 2% of the year are highlighted and projected on the Airspace skin design.*

To facilitate easy comparison between the various building skin design options, Figure 4.1.8 illustrates the behavior of the six selected case studies, highlighting the areas of the building skin design that allow over 2000 lux of daylight to pass through. The hemisphere represent the sensors that receive over 2000 lux, with those that read over 2000 lux more than 2% of the year highlighted in a darker shade. It also shows the different skin patterns and the areas of the building skin design that allow over the set threshold of light to enter.

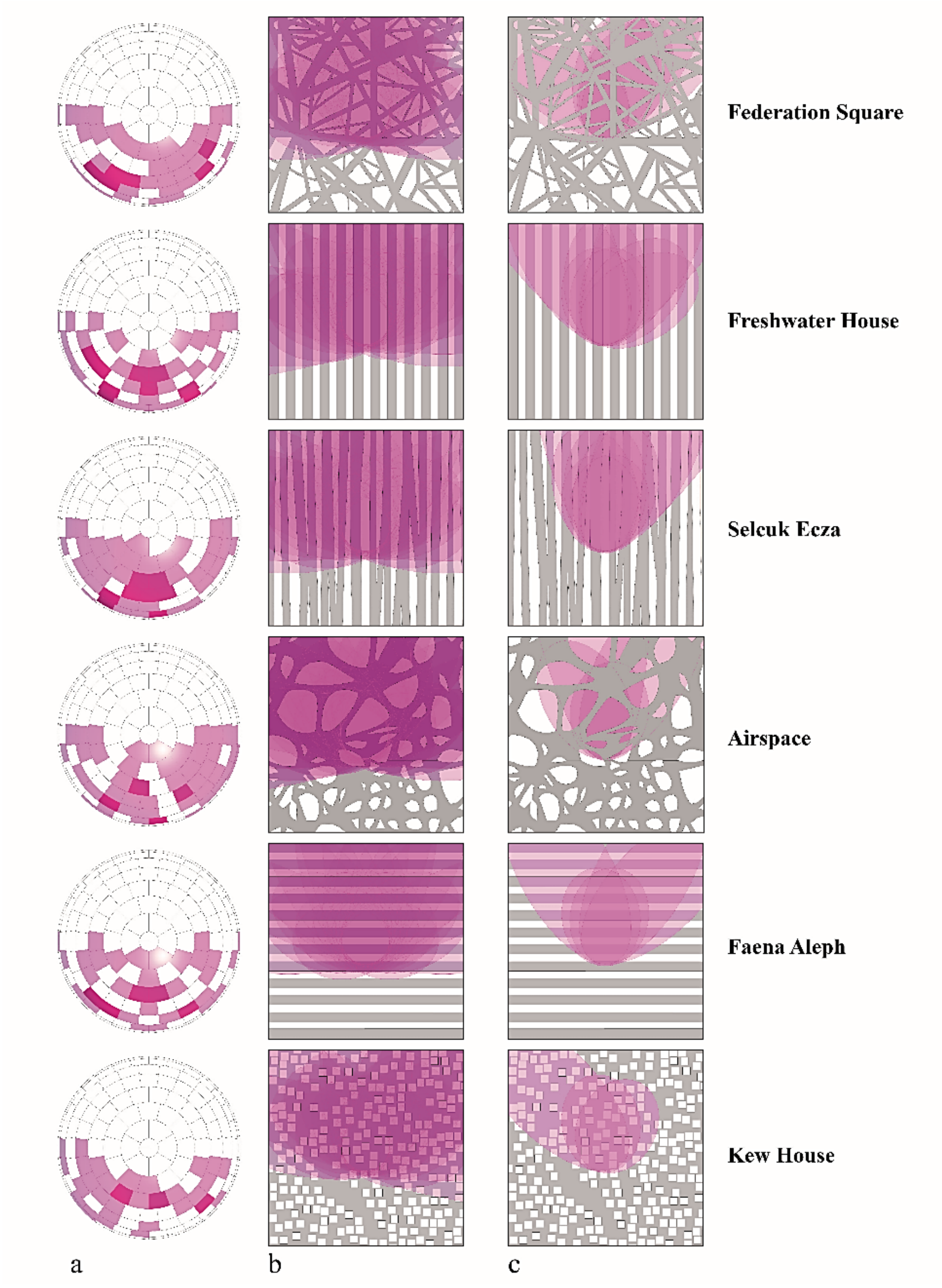


*Figure 4.1.8: a) Sensors on the hemisphere that read over 2000 lux per year. Sensors reading over 2000 lux more than 2% of the year are shown in a darker shade. B) Areas of the building skin that allow over 2000 lux of daylight to pass through per year. C) Areas of the skin that allow over 2000 lux of daylight more than 2% of the year.*

#### 4-1.3.2 Adjusting the building skin design to eliminate high illuminance infiltration

Simple methods to eliminate light penetration over 2000 lux include adjusting the design, either by increasing the density of the pattern, i.e. increasing the solid area and decreasing the openings, or by increasing the thickness of the skin design.

The Airspace building skin design was selected as an example to illustrate the effect of thickness on light infiltration (Figure 4.1.9). The initial skin design had a thickness of ½ in (1.27 cm) which resulted in substantial direct penetration of sunlight. As can be seen in Figure 4.1.10, at the end of the simulation, large areas of the skin design are highlighted, representing areas of the design that allow over 2000 lux (Figure 4.1.10 b), and similarly areas of the design that allow over 2000 lux more than 2% of the year (Figure 4.1.10 c). To eliminate light infiltration over 2000 lux, as a proof of concept, the thickness of Airspace design was increased to 12 in (30.48 cm) (Figure 4.1.9). Once the simulation was complete, the data were analyzed to evaluate the effect of thickness on light infiltration. As illustrated in Figure 4.1.10, the increased thickness of the skin (Airspace 12 in) dramatically reduced the light infiltration over 2000 lux (Figure 4.1.10 a &b). The data were further filtered to show the areas of the skin design that allow over 2000 lux more than 2% of the year (Figure 4.1.10 c). Although there are five sensors that receive light more than 2000 lux over the entire year, none of the sensors read over 2000 lux for more than 2% of the year.

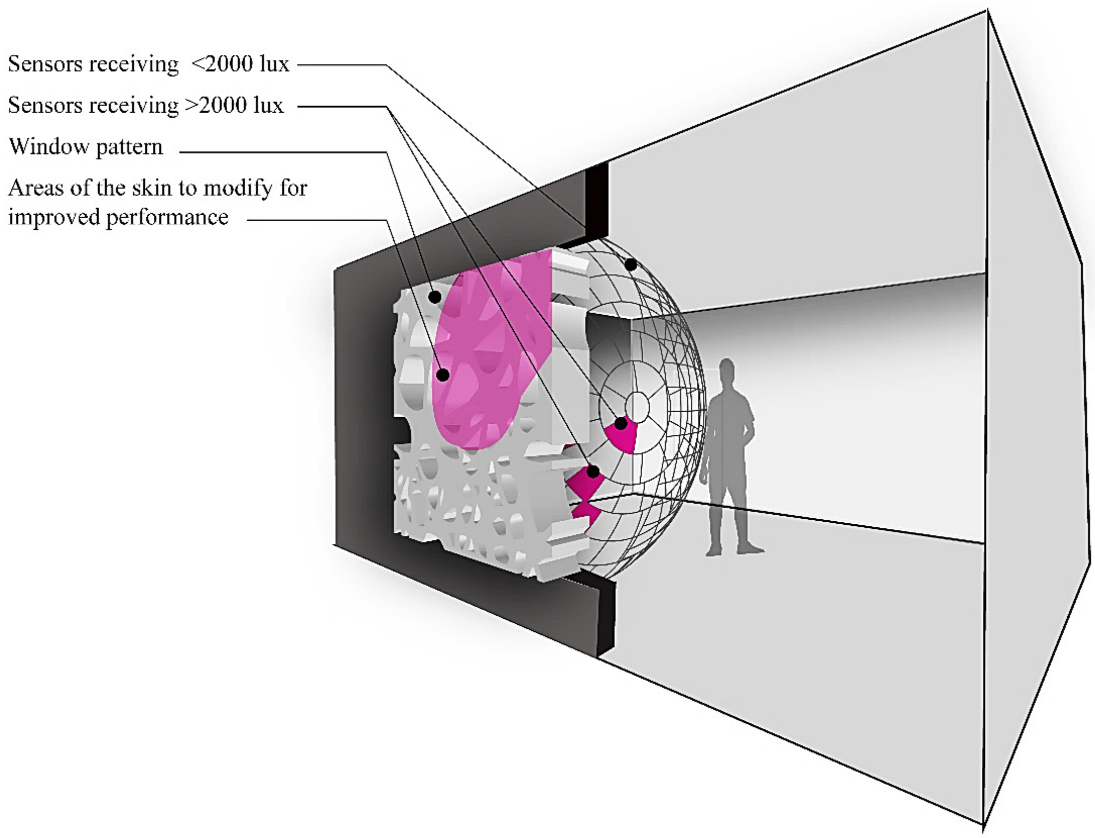


*Figure 4.1.9: Diagram of 12 in Airspace, the hemisphere location in the office space, and the highlighted areas where sensors read over 2000 lux.*

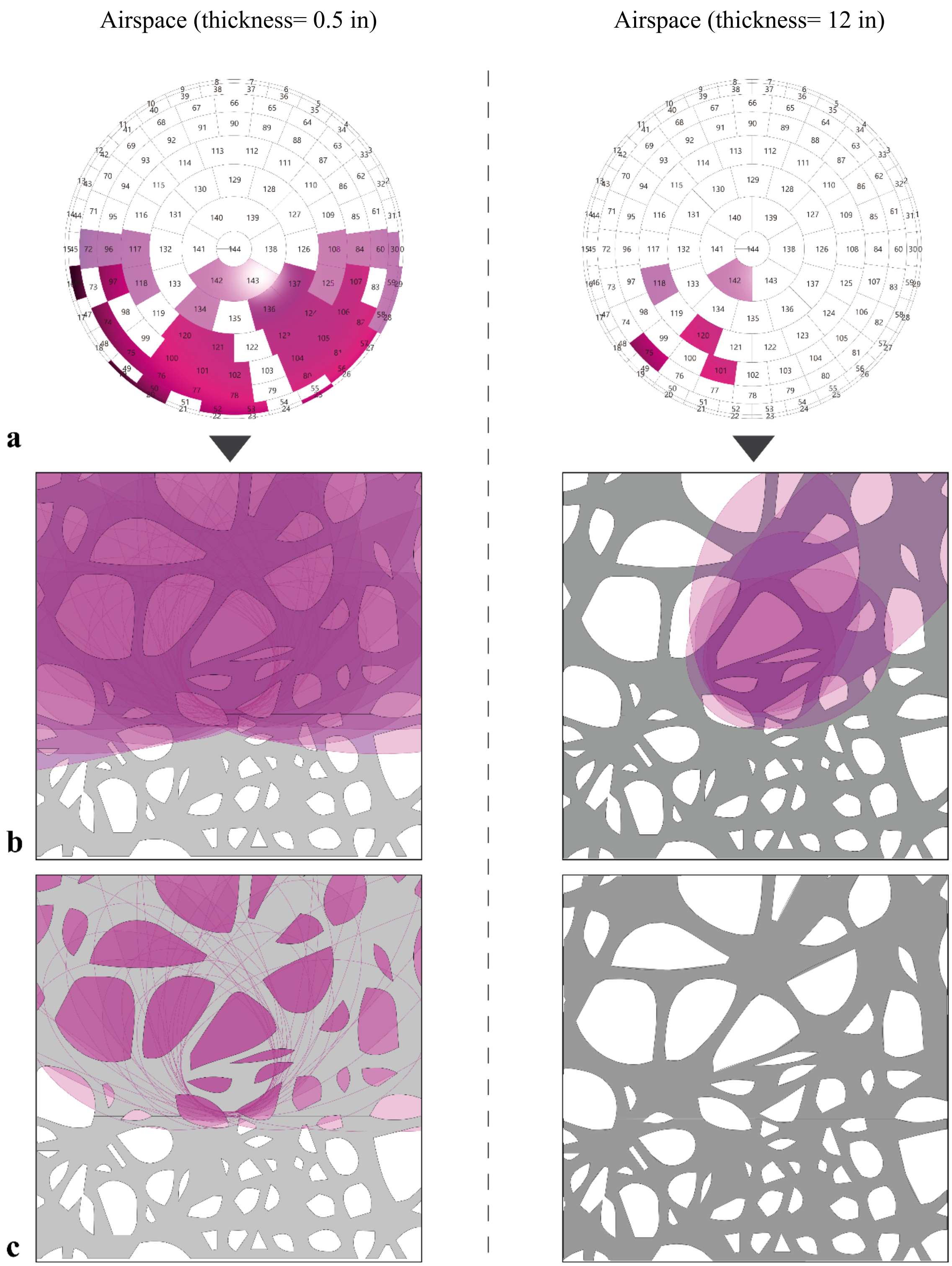


*Figure 4.1.10: a) Sensors that read over 2000 lux; those reading over 2000 lux for more than 2% of the year are shown in a darker color; b) Areas of the Airspace design pattern that allow over 2000 lux of daylight to pass through; c) Areas of the skin that allow over 2000 lux of daylight to pass through more than 2% of the year.*

4-1.3.3 From illuminance values to luminance variations

As discussed in the methods section 4-1.2.3, because the FOV of each sensor is limited and controlled, the illuminance values can be easily converted to luminance using the formula provided in Eq. 4. As a demonstration, the climate-based simulation values measuring illuminance at each sensor using the Airspace building skin pattern were converted to luminance to understand the brightness variation in the room that could be perceived by the occupants. Figure 4.1.11 shows the luminance variation on September 21st of the six selected sensors. As can be seen in the graph, sensors 132 and 141, located on the left side of the hemisphere read higher luminance values during the morning, between 9:30–11:00 am. While sensors 138 and 126, located on the right side of the hemisphere read higher luminance values in the afternoon and towards the evening, between 12:30–5:30 pm. Sensor 129, located on the upper section of the hemisphere viewing down, reads dramatically lower luminance values than sensor 135 looking upwards and reading as high as 3,700 cd/m$^2$ at 12:30 pm. Since the luminance values for each sensor over the entire year is calculated, one can easily evaluate the brightness variation in the room at different times of the year and adjust the building skin design to eliminate high values causing visual discomfort and overheating of the space, thus improving the performance of the skin design.

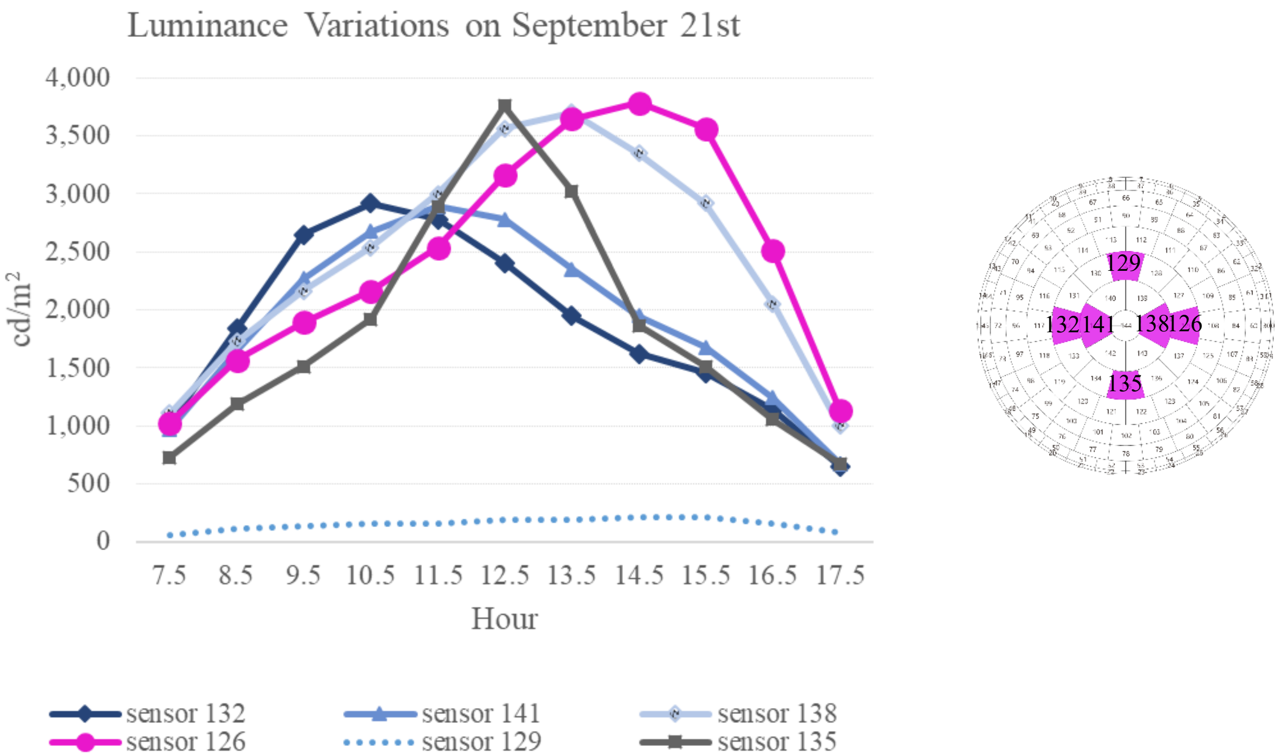


*Figure 4.1.11: Luminance variations of selected sensors measured on September 21st using the Airspace building skin pattern. The diagram of the hemisphere (on the right) illustrates the location of each sensor.*

## 4-1.4 Discussion & future work

The current method of evaluating luminance distribution using HDR renderings of four representative times in a year—March 21st, June 21st, September 21st and December 21st at noon—is not sufficient to fully aid designers in improving the performance of the building skin design for the entire year. The alternative, generating HDR renderings for every hour of the entire year (8760 hours) is time-consuming and far from efficient.

The Facade Photometry method introduces a much faster technique to measure both hourly illuminance and luminance distributions through the building facade at a specific position in the room and allows designers to capture the behavior of their design. Facade Photometry directly links measured values through simulation and facade design, and thus can be used to assess the light distribution propagating through a facade, as well as highlighting which areas of a building skin's design can be adjusted for improved performance.

For instance, if the Airspace design is aesthetically desired, the system can be analyzed and areas allowing too much light ingress can be adjusted to reduce visual discomfort associated with glare and direct radiation resulting in overheating of the space. Increasing the overall thickness of the Airspace skin pattern and its effect on light infiltration was illustrated in this research as a proof of concept, but since the areas of the skin design that allow excess light infiltration are emphasized and highlighted, it is also possible to perform local optimization by only increasing the thickness of the highlighted areas, rather than of the entire skin. This refinement could result in material savings and may produce an interesting and dynamic undulating facade design based on optimal visual and thermal performance.

However, in addition to quantitative measurements, light quality must be evaluated. Shadow patterns created by building facades' geometry can dramatically affect the visual comfort of the building's users. Although studies have looked at the effect of light distribution and variability on occupants' comfort, perception and satisfaction (Chamilothori, Wienold, & Anderson, 2016; S. F. Rockcastle, 2017), and how the effect of building skin geometry on shadow variations in an office environments is related to occupants' visual comfort (Omidfar, Niermann, & Groat, 2015), there are no known studies on the effect of building skin geometry on daylight quality and the spatial distribution of daylight over time.

Despite the progressive sophistication of daylight metrics and tools, several questions remain unanswered in the realm of building skin design and its impact on daylight ingress: what distribution of light (if any) is ideal for a specific program, such as an office space? How can designers link daylight distribution to building skin design intent? What type of data visualization will be effective to communicate the simulated values to the design team? And what metric will generate 'better' data set to inform design? Clearly, a single value cannot characterize the complexity of the entire design space. The Facade Photometry method has the potential to improve our understanding of daylight dynamics, and to connect it with the facade design process. More studies are required to find ways to consolidate the data into a more meaningful representation.

Further examination of the values associated with glare, and subjective analysis to correlate the distribution data to occupants' preferences and satisfaction, will be explored in subsequent research. The overarching goal is to develop a method that could correlate with the room occupants' visual experience and satisfaction, with the lighting, and to provide designers a concise method of assessing facade designs against a baseline using simple, intuitive logic.

Since all simulations in this study were conducted using DIVA, which uses Radiance and Daysim, the study does have limitations that must be noted here. First: because the initial calculations are illuminance-based calculations in DIVA, specular reflections (or mirror-like reflections, where the incident angle and reflection angle are the same) of the sun cannot be detected. This can be a major issue if the shading system has specular characteristics and if the values are used for glare analysis. Since none of the shading systems in this study are specular, this limitation was not an issue in this particular work. Second, Daysim uses a sun discretization of roughly 65 sun positions. This discretization and interpolation of the sun positions could lead to underestimated values for certain shading systems. Due to the sun interpolation, high luminance values can also be observed for more than one sensor at the same timestep. These problems will be studied and addressed in future work.

### 4-1.5 Conclusion

The desire to bring natural light into spaces is not merely for the purpose of completing specific tasks; therefore, it is critical to find ways to evaluate daylight distribution as it relates to perceived brightness, visual comfort, and ambiance.

Over time, lighting metrics have improved in their ability to define the distribution of daylight. However, no existing metrics are linked to interactions with facade design. Consequently, it is impossible to design facades to simultaneously maximize their capacity to transmit light for best outcomes in terms of sustainability (energy efficiency) and human comfort (thermal and glare). This research offers a new approach—Facade Photometry—for measuring light infiltration through facades, that links the structure of the facade with its impact on light transmittance. This linkage allows Facade Photometry to experimentally guide facade design, and even guide local adjustments to achieve energy efficient indoor lighting that is satisfying for the space's occupants to experience.

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# Section 2- Imagining Daylight: Evaluating Participants' Perception of Daylight in Work Environments


## Abstract

This chapter of the dissertation presents an experimental research study intended to evaluate daylight perception in work environments. The current metrics for assessing daylight in work environments involve quantifying daylight and do not provide insight into the actual appearance of the space, thus overlooking the qualitative aspects of light and their effect on occupants. Conceptual Content Cognitive Mapping (3CM), a mixed methodology, was used to obtain participants' hierarchical knowledge structure and mental model of daylight in work environments. A cognitive map of 50 participants—half architects and half non-architects—was created using 3CM. The results present a daylight lexicon and a vast selection of concepts related to physical and psychological comfort among all participants. This experiment reveals that *connectivity* and *emotional reactions* are the two dominant underlying dimensions describing daylight in work environments. The results illustrate both similarities and disjunctions between the two groups of participants regarding the selected daylight terms and characterizations. The results also indicate the need to augment current planning practices with a qualitative multi-disciplinary approach to create more pleasant working environments.

### 4-2.1 Introduction

*"The most wonderful aspects of the indoors are the moods that light gives to space"*

*Louis Kahn*

Our mood and perception of a space is influenced by the surrounding environmental cues, such as the four-dimensional daylight patterns. This fourth dimension- its dynamics, ephemerality and unpredicted shadows, are some of the qualitative aspects of daylight that are most challenging to evaluate when measuring the effects of daylight on people's perception, satisfaction, mood and wellbeing.

Designing a comfortable environment is a complex and multi-faceted process which necessitates more than meeting the required lighting standards and recommendations; it also requires an understanding of the features valued by the people for whom the space is designed. Therefore, it is critical for designers to identify what users find important, and to be able to evaluate their unique perspectives, and ideas. Additionally, current lighting metrics measure the amount of light falling on a two-dimensional planar surface at desk level and focus on providing light availability adequate to complete a certain task. However, these metrics disregard the qualitative aspects of daylight that influence how people perceive their work environment. Measurement of illuminance distribution, which is only one aspect of daylight, will not produce a meaningful value of how that particular environment is perceived by its user. This shortcoming makes it difficult for designers to consider the qualitative characteristics of daylit environment during the design phase. Furthermore, there is no shared consensus among professionals on what the appearance of a workspace should be. Should it be bright and lively, or diffuse and calming?

Should the space have uniform lighting? When it comes to daylight, what is important to users? What are their expectations, their assumptions, and the features important to them? Assessment of the intangible and subjective qualities of light is commonly conducted using a survey study with semantic differential rating scales (Amundadottir, Rockcastle, Khanie, & Andersen, 2016; Cetegen , D .; Veitch , J . A .; Newsham, 2008; Chamilothori, Wienold, & Andersen, 2016; Flynn, Spencer, Martyniuk, & Hendrick, 1973; Mahdavi & Eissa, 2002). A semantic differential rating scale is a multidimensional tool for measuring the meanings and values of concepts or constructs. In 1957, Charles E. Osgood and colleagues published a book presenting semantic differentials as a technique to measure meaning, and rating procedures as a way of evaluating the intensity and the directionality of the concepts rated by each participant (Osgood, Suci, & Tannenbaum, 1957). In this book, *The Measurement of Meaning*, the authors explained that the use of semantic differential as a technique for measuring meaning was developed based on an earlier study on "synesthesia", which they described as " a phenomenon characterizing the experiences of certain individuals, in which certain sensations belonging to one sense or mode attach to certain sensation of another group and appear regularly whenever a stimulus of the latter type occur" (Osgood et al., 1957). The authors further explained that this phenomenon was not unique to a person; rather, it was experienced by many college students who participated in their study, and is evident in our everyday metaphors, for instance, "...A happy man is said to feel 'high', a sad man 'low'; the pianist travels 'up' and 'down' the scale from treble to bass, souls travel 'up' to the good place and 'down' to the bad place; hope is 'white' and despair is 'black'" (Osgood et al., 1957). Further studies of such relations have revealed that such relationships are also largely not dependent upon culture (Kittler, Kocifaj, & Darula, 2012; Osgood et al., 1957).

Semantic differential scales, introduced by Osgood and colleagues as a way of using adjectives to measure perception, experience, cognition and emotion, have influenced the field of psychology. In addition to psychologists, many researchers in various disciplines, including architects, lighting designers and researchers have adopted the same method. In fact, the most commonly used technique for evaluating participants' perceptions in architectural and lighting research studies is semantic differentials (Lavrakas, 2008).

In the 1970s, Küller used a semantic differential scaling method to evaluate visual perception in architecture (Küller, 1991). He concluded that there are eight dimensions which characterize the visual appearance of interior environments: "pleasantness", "complexity", "unity", "enclosedness", "potency", "social status", "affection" and "originality". Küller developed a standardized document which comprised 36 seven-point unipolar adjective rating scales for studies related to the evaluation of visual perception in the built environment. Küller's list includes adjectives such as "pleasant", "lively", "open", "simple", "lavish", "modern", "boring", "stimulating", "airy", "potent", "surprising", etc. (Küller, 1991).

At the same time, Flynn et al. published a study on using semantic differential and factor analysis to study the effect of light on impression and behavior (Flynn et al., 1973). By altering the appearance of a conference room using six different lighting configurations and 34 semantic differential scales they concluded that people prefer lit environments that appear "bright" and "interesting" (Flynn et al., 1973). Flynn's questionnaire consisted of 18 bi-polar adjectives: "pleasant/unpleasant", "like/dislike", "bright/dim", "radiant/dull", "spacious/cramped", "interesting/monotonous", etc.

A recent experimental study by Rockcastle et al. conducted with virtual reality headsets, highlighted the relationship between the design of architectural spaces, lighting and users' emotional responses (Rockcastle, Chamilothori, & Andersen, 2017). Subjective evaluations of simulated daylight architectural environments were collected and were compared to image-based measures related to impressions of visual interest. By using semantic differential rating scales, the authors concluded that impressions of “pleasant”, “interest” and “excitement” can be predicted in immersive scenes. Since Flynn’s interim study, there have been numerous research studies on the perception of a lit environment and/or the link between occupants’ perceptions and luminance distribution (Rockcastle & Andersen, 2012; Tiller, 1995; Van Den Wymelenberg, Inanici, & Johnson, 2010).

An important aspect of using semantic differential as a tool is the selection of appropriate descriptors or concepts. The dimensionality of the scale system determines the intensity and position of the concepts; thus, the full sampling of descriptive scales becomes critical in any subjective study. With that in mind, Osgood and colleagues have used multiple methods to obtain descriptors. In one study, the selection criterion was the frequency of usage of the concepts; they selected forty nouns from a list of stimuli which were rapidly read to 200 undergraduate students. The participants were instructed to note the first descriptive adjective that came to their mind after hearing each stimulus noun (e.g., CAT-fuzzy; SHIP-big; BABIES-cute; HERO-strong). The data were then analyzed for the frequency of occurrence of all adjectives, separated into sets of polar opposites, and used for further study. Another method used by Osgood’s team to gather semantic dimensions used *Roget’s Thesaurus* (1941 edition) as a source. Osgood and a colleague each went through the thesaurus independently, selecting one pair of polar terms from the list of adjectives that were the most representative terms from each polar paired category. The two lists generated by Osgood and his colleague were then combined, and through an elimination process, this combined list was reduced to a sample of 289 adjective-pairs. They further reduced the samples from 286 to 76 through a sorting procedure with 18 participants (Osgood et al., 1957).

Although Flynn's scales have been the foundation of many questionnaires developed for lighting research (Boyce & Cuttle, 1990; Newsham, Marchand, & Veitch, 2004), the researchers conducting these studies never discussed in their papers how the scales were selected, and thus never standardized the lexicon used. One thing is clear—these scales were developed and intended for assessing artificial lighting and are not necessarily appropriate for studies on daylight.

In 2008, Vogels constructed a questionnaire measuring the atmosphere of interior environments perceived by human observers (Vogels, 2008). Vogels chose the term "atmosphere" rather than "mood" because atmosphere "is a subjective impression of the environment related to the *expected* effect on mood, but it does not necessarily correspond to the *actual* effect on mood" (Vogels, 2008). In her study, rather than relying on previous semantic differentials and terms, she first collected terms that people used to describe the atmosphere of an environment and then used those terms to create a questionnaire based on the collected terms. A list of 38 terms, in both Dutch and English, was presented as concepts to study observers' experience of an environment. The list includes terms such as "detached", "terrifying", "cozy", "exciting", "pleasant", "warm", "cheerful", "stimulating", "boring", "spatial", "romantic", "relaxed", "uncomfortable", "lively", "intimate", etc. Similar to Flynn, this research focused on artificial lighting, rather than daylight. Although the list of terminology created by Vogels can be used for daylight studies, as they are related to the overall atmosphere of the environment, it is also important to understand how daylight in work environments is experienced by users and what lexicon they use when describing daylight in office environments.

Notably, “There is evidence…that the beliefs people hold about lighting can influence their performance and mood” (Veitch, Hine, & Gifford, 1993). People’s perceptions, decisions and behavioral patterns are directed by their “mental models” (S. Kaplan & Kaplan, 1982). These models embody their knowledge structures encompassing their “beliefs” and understanding about the world. These assumptions provide the “framework for interpreting new information and for determining appropriate responses to new situations” (A. R Kearney & Kaplan, 1997). Once a problem and the factors contributing to it are understood, various ways can be found to address it. However, in the case of daylight in workspaces, user perception and expectations are an unknown factor. In addition, daylighting and lighting design are complex realms involving many interdisciplinary teams whose knowledge, understanding and overall mental models of the problem may vary. Externalizing everyone’s understanding and mental map would allow the team to compare and discuss shared beliefs and highlight areas of disagreement (A. R Kearney & Kaplan, 1997). Bringing these differences or common beliefs out into the open would simplify the decision-making process tremendously. When these differences are overlooked or cannot be communicated, the result can be the design of an uncomfortable and unpleasant environment.

In this research study, Conceptual Content Cognitive Mapping (3CM) was used to collect terms that people often use when describing daylight in their work environment. 3CM is a mixed research method for understanding the hierarchical knowledge structure of an individual’s mental model (Anne R Kearney, 2015). It is a unique technique that focuses on conceptual content and past experiences rather than visual images or physical spaces, highlighting a user’s “expectations”, “beliefs”, “values”, and “assumptions” about the world. Instead of designating and detecting what the users would like to see in a working environment from examples, it highlights “what is already in an individual’s head, related to a particular topic”—in this case, daylight in their workspace (A. R Kearney & Kaplan, 1997). The result underlines the daylight terms that participants believe are important, as well as illuminating the organization and structure of the concepts (Anne R Kearney, 2015).

Although this method has been used to investigate a variety of topics, including low-income housing (Wells, 2005), promoting carpooling (Anne R. Kearney & de Young, 1995), sustaining a walking routine (Duvall & De Young, 2013), coping with illnesses and the psychological impact of cancer (Lehto, 2004), and new parents' feeling of competency (Sink, 2001), this research study represents the first use of 3CM with respect to daylighting in workspaces.

### 4-2.2 Method

This study sought to explore an alternative pathway to collect terms that people use to describe daylight in their work environments and to understand participants' understanding of daylight by externalizing their mental models using 3CM. This research was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (IRB-HSBS, Case Number: HUM00128760).

#### 4-2.2.1 Participants

This research study was broken down into two interview phases: the first applied the open-ended 3CM method to collect terms that people use to describe daylight in work environments, while the second used the structured 3CM method to assess the relationship between terms and the frequency of the terms used among participants. All participants in both phases were unpaid volunteers over 18 years of age, recruited by email or in person.

- *Phase 1: Open-ended 3CM*

In the open-ended 3CM phase, participants were asked to write down terms or descriptors they use in describing daylight in their work environments—aspects of daylight that are important to them, or daylight concepts they like or dislike in their workspace. In this phase, fifteen people participated (53% female, 46% male), and each created a list of terms relating to daylight in a working environment that they commonly use and perceived as important. Each session lasted no more than 15 minutes.

- *Phase 2: Structured 3CM*

In the structured 3CM phase, individual participants chose terms from the list generated in the open-ended phase and were invited to add their own terms if they were not on the list. A total of 50 participants (60% female, 40% male) were interviewed in this phase. Half of the participants (25) held an architectural degree or were studying architecture, and thus were classified as architects in this study, and the other half (25) had no formal education in architecture. Each session in this phase lasted no more than 20 minutes.

The final list following this phase had a total of 58 terms.

#### *4-2.2.2 Procedure*

The open-ended 3CM procedure involved the following steps:

- *Posing the question*: Because the individual mental model needs to be "activated" though a scenario, this method starts with a series of questions. Participants were asked to "Imagine a friend is designing a workspace and wants to know your opinion on what makes for the best daylighting conditions. What aspects of daylight do you like or dislike? What should she, the designer, consider? Think about explaining your ideas about daylight to your friend. What would you say, and what keywords/concepts would you mention when discussing this issue?"

- *Terms:* After hearing the questions, participants wrote down terms that they would use to describe daylight in their work environments, terms that they felt were important and relevant to the issues of daylight in interior workspaces. They were asked to write each term on a separate blank card.
- *Grouping items:* Participants were asked to group the cards into categories based on what terms they thought belonged together.
- *Prioritize the groups:* Finally, participants were asked to rank the groups based on their importance.

The structured 3CM procedure involved the following steps:

- *Posing the question*: In a manner identical to that described for the open-ended procedure.
- *Selecting terms:* In the structured 3CM, participants selected terms from the list created by the first phase and were invited to add other terms they felt were important and were not listed on the provided list. Each term selected was written on a separate blank card.
- *Grouping terms:* As described for the open-ended procedure.
- *Labeling groups:* Participants were then asked to come up with a phrase to describe each of their groups. The label for each group was written on a blank card and placed above the group of terms.
- *Prioritize the groups:* As described for the open-ended procedure.

*4-2.2.3 An example of structured 3CM: one participant's mental map*

As an example of structured 3CM, it may be useful to see a participant's mental map. This person had a list of 58 terms from which to choose, as well as the option to add words of his/her own. This participant selected fourteen out of the 58 concepts provided, and categorized them into three groups based on what s/he thought belong together. S/he then labeled the groups and ranked each group based on its perceived importance. Table 4.2.1 illustrates how this participant ranked each group, the labeling of the groups, and the concepts selected.

*Table 4.2.1. Example of a participant's map.*

| Rank | Labels | Concepts in each group |
|---|---|---|
| 1 | Feeling | Comfortable Bright Energizing Warmth Calming Relaxing Color |
| 2 | Connection | Directionality View Sense of time/season Sunny Connection to outside |
| 3 | Energy | Passive heat Energy efficiency |

*4-2.2.4 Data collection and analysis*

Data for this study were collected via in-person interviews conducted in Ann Arbor and Grand Rapids, Michigan. The data were analyzed using descriptive statistics and exploratory factor analysis. Exploratory factor analysis identifies the relationship between the studied variables. It is used to reduce a large set of data to a smaller set of variables to analyze the underlying relationship between them (Chow, Cappelleri, & Gerber, 2010). The factor analysis is based on the similarity matrix $S(i, j)=C(i, i)/\text{sqrt}\ (C(j,j))$, where $C(i, j)$ is the number of participants who selected both term $i$ and term $j$. Thus, the factor analysis results are determined by the pattern of co-selection (pairs of terms selected by one participant) of pairs of terms by the same participant. Exploratory factor analysis was performed using "Factanal" in the "Stats" package of R software (version 1.2.1335) (Team, 2019).

## 4-2.3 Results

This section presents results of both phases, open-ended and structured 3CM, and also highlights the similarities and differences between the mental maps of architects and non-architects.

#### 4-2.3.1 Phase 1: open-ended 3CM

In the initial open-ended 3CM study, a list of concepts was created by collecting terms that participants used to describe daylight in work environments. After the questions were read to the participants, they wrote down terms that they would use to describe daylight in their workspace, or that they found relevant to daylight in work environments. A total of 86 terms were collected and were reduced to a final list of 58 terms by removing identical terms or those with similar meaning. Table 4.2.2 illustrates the final list of 58 terms generated in the open-ended phase, which was later used in the second phase, structured 3CM.

*Table 4.2.2. List of daylight terms generated by participants in phase 1.*

| **Terms related to daylight in workspace:** | | | |
|---|---|---|---|
| Happiness | Mood | Strong | Stark |
| Directionality | Spacious | Bright | Less energy use |
| View | Interesting | Southern Exposure | Awake |
| Glare | Complex | Calming | Passive heat |
| Contrast | Shades | Dynamic | Cozy |
| Color | Excessive | Intensity | Wellness |
| Physical access to a bright space | Warmth | Discomfort | Diffuse |
| Beautiful | Adequate | Simple | Heat |
| Relaxing | Enough light to see | Disturbing | Pleasant |
| Energizing | Alive | Inviting | Refreshing |
| Renewable Energy | Harsh | Uniform | Unbalanced |
| Natural/ not artificial | Promote growth | Cheerful | Exciting |
| Reduce Monotony | Ambiance | Sunny | Glazing |
| Shadows/shadow patterns | Energy Efficiency | Connection to outside | |
| Sense of time/season | Dim | Comfortable | |

Intriguingly, more than 50% of the terms generated by the participants in the first phase were related to emotional reactions or the affective influence of daylight on people, such as “energizing”, “relaxing”, “exciting”, “cozy”, “calming”, “happiness”, etc., while only 10% of the terms generated regarded issues and concerns about daylight in workspaces, such as “glare”, “harsh”, “heat”, etc.

#### 4-2.3.1.1 *Terms, Categories and Labels*

<u>Phase 1: open-ended 3CM</u>

Participants in this phase generated between 5–14 terms related to daylight (mean = 7.8, SD = 2.51) and grouped them into 3–5 categories (mean = 3.2, SD = 0.79). Of the 86 terms that were originally collected, 14 terms were ranked as number one—the most important concepts to consider when working with daylight in workspace. The highest ranked terms are listed in Table 4.2.3. It is important to point out that out of all 14 highest ranked terms only one term, “glare”, is regarded as a negative aspect of daylight in workspace.

*Table 4.2.3: Highest ranked terms in phase 1.*

| | | | | |
|---|---|---|---|---|
| Happiness | Sense of time | Shadows | View | Relaxing |
| Glare | Energizing | Warmth | Connection to outside | Color |
| Shades | Mood | Ambiance | Dynamic | |

### 4-2.3.2 Phase 2: structured 3CM

In the second, structured, phase of this study, 50 participants selected terms from the provided list of terms to describe daylight in office environments. Table 4.2.4 shows the list of terms and percentage of participants who selected each term (100*number of participants selecting a particular term / total participants). Among all selected terms, “natural/not artificial” (50%), “connection to outside” (46%), “glare” (40%), “bright” (40%), and “warmth” (36%), were selected the most often among all participants (N = 50). Terms such as “interesting”, “complex”, “excessive”, “discomfort”, “simple”, “disturbing”, “stark”, “unbalanced”, and “glazing” were not selected by participants in this phase.

*Table 4.2.4: Daylight terms with percentages of participants who selected each term in phase 2.*

| **Terms related to daylight in workspace:** | | | |
|---|---|---|---|
| Natural (50%) | Uniform (18%) | Heat (10%) | Physical access to a bright space (4%) |
| Connection to outside (46%) | Wellness (18%) | Spacious (8%) | Enough light to see (2%) |
| Glare (40%) | Color (14%) | Harsh (8%) | Dim (2%) |
| Bright (40%) | Beautiful (14%) | Energy Efficiency (8%) | Strong (2%) |
| Warmth (36%) | Mood (14%) | Southern Exposure (8%) | Exciting (2%) |
| Energizing (34%) | Shades (14%) | Dynamic (8%) | Interesting (0%) |
| Sense of time (28%) | Alive (14%) | Awake (8%) | Complex (0%) |
| Sunny (24%) | Pleasant (14%) | Reduce Monotony (6%) | Excessive (0%) |
| Diffuse (24%) | Passive heat (12%) | Promote growth (6%) | Discomfort (0%) |
| Happiness (22%) | Refreshing (12%) | Less energy use (6%) | Simple (0%) |
| View (22%) | Relaxing (10%) | Contrast (4%) | Disturbing (0%) |
| Calming (22%) | Shadow patterns (10%) | Renewable Energy (4%) | Stark (0%) |
| Ambiance (20%) | Adequate (10%) | Intensity (4%) | Unbalanced (0%) |
| Directionality (18%) | Cheerful (10%) | Inviting (4%) | Glazing (0%) |
| Comfortable (18%) | Cozy (10%) | | |

To illustrate the importance of each term, a visual representation of the terms that were selected more than once is shown in Figure 4.2.1. In this figure, the size of each word indicates its frequency; therefore, the more often the term was selected, the larger and bolder it appears. Terms such as “natural”, “connection to ouside”, “bright”, “glare”, “warmth” and “energizing” were among the most frequenlty selected terms.


*Figure 4.2.1: A visual representation of the terms. The size of each term represents its frequency or perceived importance among participants.*

4-2.3.2.1 *Terms, Categories and Labels*

<u>Phase 2: structured 3CM</u>

Participants in the structured phase selected between 3–27 terms (mean = 7.46, SD = 4.1), and grouped the terms into 1–4 categories (mean = 2.6, SD = 0.8). Each participant labeled the categories and ranked them based on their understanding of the most important concepts to consider regarding daylight in a workspace. Examples of the most common categories and the associated terms in each category are shown in Figure 4.2.2.

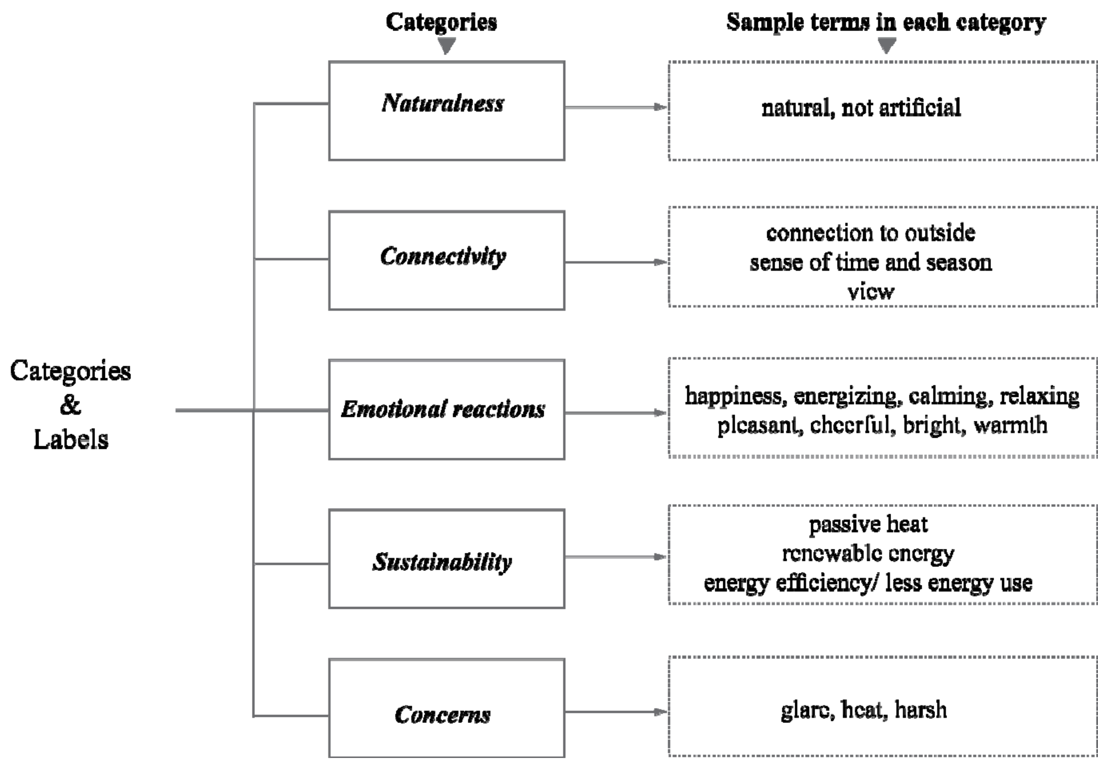


*Figure 4.2.2: Examples of terms that were associated with a sample of categories generated among participants in the structured phase (N = 50).*

After grouping the terms into different categories, participants ranked the categories in order of their importance (1 = most important). The daylight terms selected by five or more people that are ranked as the most important concepts to consider in work environments are "connection to outside" (N = 26%), "natural/not artificial" (N = 22%), "warmth" (N = 22%), "bright" (N = 20%), "energizing" (N = 16%), "sense of time and season" (N = 14%), "happiness", "directionality", "view", "comfortable", and "calming" (N = 12%), "beautiful", "pleasant", "glare" and "color" (N = 10%).

The grouping of the terms is an important step, as it reveals the concepts that go together in participant's minds. When participants label each group, they indicate why they grouped those concepts together. Finally, by ranking each group, each participant specifies which group they consider the most important to consider in design of an office space. This information can be used to understand what the participants perceive as important, what they know about lighting in office environment, and what is missing in the larger picture.

#### 4-2.3.2.2 *Exploratory Factor Analysis of Structured 3CM*

Exploratory factor analysis of terms selected by ten or more people (out of 50) revealed weak patterns of co-selection. The components of the factor analysis defined through their loadings showed two dominant factors, explaining 24% of the variance. The first factor reflects the dominant terms “view”, “connection to outside” and “sense of time and season” co-selected by the participants, and the second factor reflects the dominant terms “energizing”, “sunny” and “happiness”. Given that the common category labels shown in Figure 4.2.2 include the terms in the first and second factors, the factors could be interpreted as *connectivity* and *emotional reactions.* The two factors and their loadings are listed in Table 4.2.5.

*Table 4.2.5: Factor analysis: co-selection of terms and their loadings.*

| **Loadings:** | **Factor 1** | **Factor 2** |
|---|---|---|
| Happiness | | **0.519** |
| View | **0.604** | 0.123 |
| Glare | | |
| Energizing | 0.227 | **0.680** |
| Natural | -0.149 | -0.145 |
| Bright | 0.187 | 0.271 |
| Ambiance | | -0.321 |
| Sense of time or season | **0.894** | -0.112 |
| Sunny | 0.139 | **0.359** |
| Connection to outside | **0.655** | |
| Warmth | 0.152 | 0.255 |
| Diffuse | | -0.284 |
| Calming | 0.162 | 0.276 |
| | **Factor 1** | **Factor 2** |
| SS loadings[1] | 1.792 | 1.311 |
| Proportion Variance | 0.138 | 0.101 |
| Cumulative Variance | 0.138 | 0.239 |

4-2.3.2.3 *Architects' vs. non-architects' mental maps*

The final study sample included 50 participants, with an equal distribution of architects and non-architects. The responses from all subjects were divided between architects and non-architects to observe if any dissimilarities existed between the two study groups due to their education and professional experiences. Architects selected eight terms on average (SD = 5.14) and grouped them into 1–4 categories, while non-architects selected an average of seven terms (SD = 2.9) and grouped them into 1–4 categories.

[1] Sum of Squared Loadings. This information is used to determine the value of a particular factor. Typically, SS loading greater than 1 is worth keeping (Ford, 2016).

The subset of terms that were frequently selected, by five or more architects in the structured phase—from among the list of 58 daylight terms—are listed in Table 4.2.5, and those selected by five or more non-architects are listed in Table 4.2.6.

*Table 4.2.6. Most frequently selected terms among architects, N = 25.*

| **Most frequently selected terms and the percentage of participants who selected each term** | | | |
|---|---|---|---|
| Natural/not artificial | 48% | View | 24% |
| Connection to outside | 40% | Ambiance | 24% |
| Bright | 40% | Wellness | 24% |
| Glare | 36% | Energizing | 20% |
| Uniform | 36% | Shades | 20% |
| Warmth | 32% | Mood | 20% |
| Diffuse | 32% | Sunny | 20% |
| Sense of time/season | 28% | Alive | 20% |
| Happiness | 28% | Calming | 20% |
| Comfortable | 28% | | |

*Table 4.2.7. Most frequently selected terms among non-architects, N = 25.*

| **Most frequently selected terms and the percentage of participants who selected each term** | | | |
|---|---|---|---|
| Natural /not artificial | 52% | Sense of time/season | 28% |
| Connection to outside | 52% | Sunny | 28% |
| Energizing | 48% | Directionality | 24% |
| Glare | 44% | Calming | 24% |
| Bright | 40% | View | 20% |
| Warmth | 40% | | |

"Natural/not artificial" and "connection to outside" were the most frequently selected terms among both architects and non-architects. Though many similarities are apparent between architects and non-architects in respect to the terms selected, there are a few terms that were not common to both groups. However, differences did emerge. While 36% of architects selected the term "uniform" as an important consideration, non-architects did not perceive "uniform" as important ("uniform" = 0% among non-architects). Similarly, 24% of non-architects perceived "directionality" as important and relevant to daylight in workspaces, a term that was not highly selected among architects—only three architects (12%) selected the term "directionality" as important. In respect to categorization of daylight terms architects grouped the terms "sunny", "bright" and "glare" together, while non-architects only grouped "bright" and "sunny" and did not categorize "sunny" with "glare". Additionally, architects grouped "diffuse" and "ambiance", while non-architects grouped "ambiance" with "calming".

The results from the exploratory factor analysis revealed no clear differences between architects and non-architects regarding patterns of co-selection of the terms. The biplot of the exploratory factor analysis shown in Figure 4.2.3 illustrates the factor scores and loadings of each term co-selected by 10 or more people. Scores provide information about the population, how a given person relates to the each of the factors, while loading provide information about the variables and explains how a given variable relates to the different factors.

Terms whose loadings have the same sign (both positive or both negative, e.g. view and connection to outside for factor one) will tend to be co-selected, while terms whose loading have opposite signs, e.g. energizing and ambiance, will tend to be "anti-selected". Terms that load similarly on the first or second factor tend to be co-selected by participants. Interestingly, as can be seen in Figure 4.2.3, scores for factor one for this data set is separated into two clusters with scores greater or less than 0.5; this gap separates all participants into two groups, a group that co-selected terms with strong loadings on factor 1, and those who did not. Architects and non-architects who scored less than 0.5 in factor 1 tend to co-select terms such as "natural", "bright", "glare", "calming" and "warmth", which were labeled as daylight terms related to *comfort*.

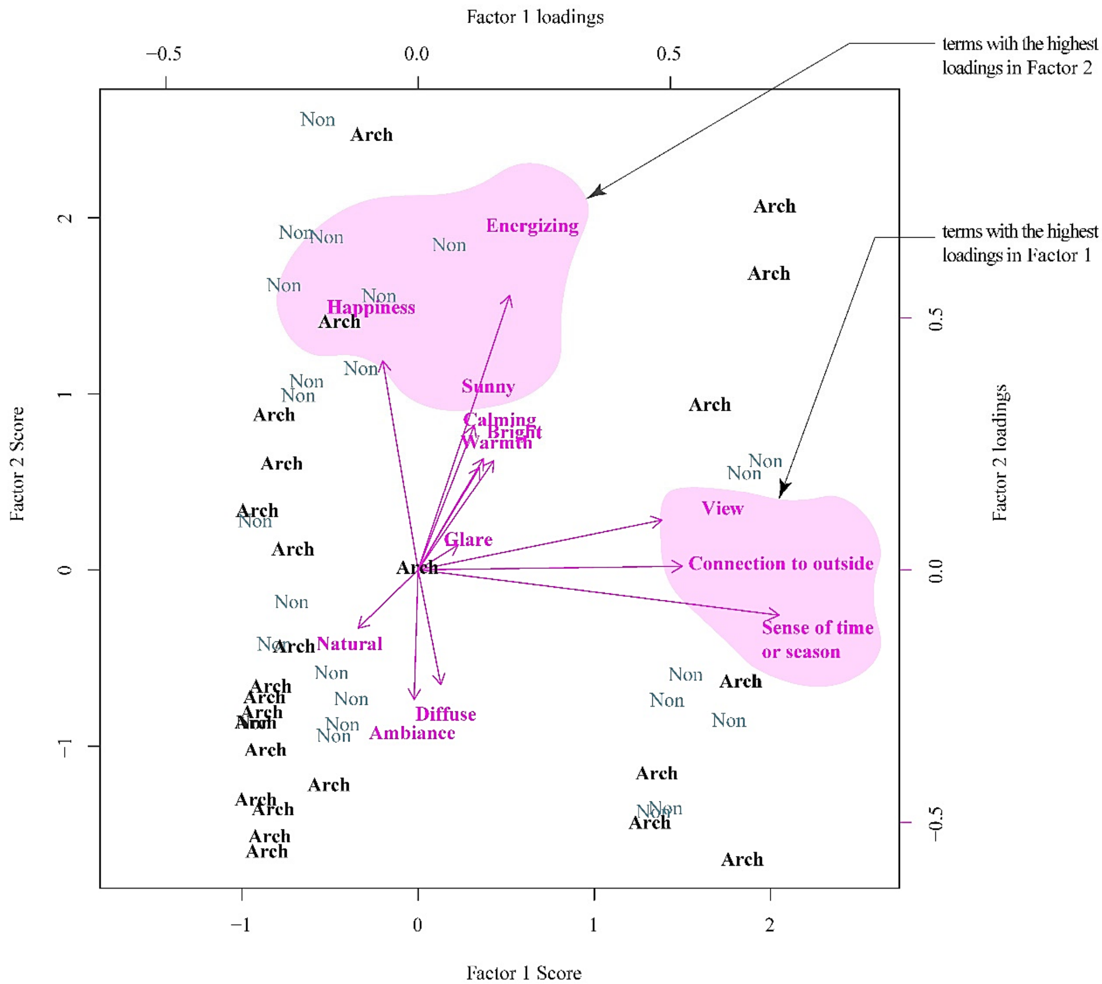


*Figure 4.2.3: Biplot of the exploratory factor analysis displays both the loadings and the factor scores (Architects = "Arch", non-architects = "Non").*

## 4-2.4 Discussion and Conclusion

In a recent post-occupancy evaluation survey of 44 occupants in two LEED platinum buildings, the authors discussed that issues with green design that do not always translate to comfortable design. According to Hedge, "The current emphasis is on meeting energy goals. You can meet those, but if people are uncomfortable you are losing their support and their productivity. The message is, you can be green, but you also have to be human" (Hedge & Dorsey, 2013). Conflicts of ideas, and perception between what designers have presumed and what users prefer has resulted in many unpleasant environments. Humans move through a dynamic world where light, something to which we respond strongly, is always changing. Despite this, research on the effect of light on users' perceptions and satisfaction in workspaces has been limited.

Although the selection of many daylight descriptors and the categorization of terms were similar among architects and non-architects in this study, there were small discrepancies in the categorizations of various items that are worth investigating, including the items "uniform", "bright", and "sunny".

The concept of light "uniformity", in particular, has been studied by researchers with inconsistent and conflicting results. For example, in a subjective research study of a conference room that could be lit in six different ways, the authors concluded that people prefer lit environments that appear "bright" and "interesting", concepts that are related to light characteristics of "non-uniformity" (Flynn et al., 1973). However, in a recent research study of aesthetic perceptions of occupants using diverse daylighting systems, the authors concluded that spaces with better light distribution along the ceiling and on the work area resulted in higher preference ratings among participants due to a "positive perception of light uniformity" (Moscoso & Matusiak, 2017). They also concluded that although view has been regarded as one of the most important factors in users' preferences, its effect on users' perceptions was smaller than light distribution (Moscoso & Matusiak, 2017).

Other researchers have also discussed the link between light uniformity and positive appearance of an environment (Littlefair, Aizlewood, & Birtles, 1994). Though light uniformity and view were generated terms in this research study, uniformity was only selected by the architects (18% overall selection). Non-architects did not select uniformity as an important characteristic in their working environment. In this study, “view” had an overall selection of 22%, selected by 20% of non-architects and 24% of architects.

On average, non-architects did not associate “sunny” with “glare”. The idea that “sunny” and “glare” are grouped together among architects could suggest that architects believe that spaces should have uniform lighting devoid of any direct sunlight, a workspace that may be considered undesirable by many users. The concept of “glare” was selected as an important consideration among both groups; interestingly, though 36% of architects and 44% of non-architects selected the word “glare”, they did not select “discomfort” or “disturbing”.

Other research studies have also discussed the importance of the location of sun patches or shadow patterns and their effect on users’ appreciation of the space (Wang & Boubekri, 2011). In this research study, the concept of shadow patterns, though selected by a few architects, was not widely selected among either groups (1 percent overall selection), however, light “directionality” was selected by 24% of non-architects. This distinction should not lessen the importance of concepts such as “uniform” or “shadow patterns”; nonetheless, it highlights the contrast between the terms that participants select when observing a scene, virtually or physically, versus their ideal workspace based on prior experiences and their mental model.

There are clearly some differences between architects and non-architects in terms of both selecting terms that they perceived are important and how the terms were grouped. These differences have been attributed to the professional education of architects (Hubbard, 1996; IMAMOGLU, 2000; Montañana, Llinares, & Navarro, 2013). For example, most often, architects learn to associate direct sun with danger of glare, or that light uniformity results in a comfortable workspace. Design training and the professional experiences of architects alter their understanding of spaces and results in different criteria and values (Groat, 1982).

This research study used the 3CM method to gain insight into the personal experiences and perspectives of architects and non-architects regarding daylight in work environments. The result provides a lexicon that can be used in subjective studies related to daylight and also offers a more holistic view of perception about daylight, which can help designers understand its effect on subjective assessments of work environments.

Many of the concepts discussed in this study are subjective, related to emotions and feelings; thus, it is difficult for designers to directly relate them to their design. The terms selected in this study pose a series of questions concerning design: How does one design for "warmth", "ambiance" or "calming"? What is the threshold of a "bright" space? How "bright" does a space need to be to evoke a certain emotion? How can the discrepancy between how spaces are designed versus how they are experienced be evaluated and minimized?

Participants' selection and categorization of the daylight terms can be used to understand what individual preferences are, what they know about daylight, what they perceive as important, and what might be missing from their knowledge structure (Veitch et al., 1993). Terms such as "natural/not artificial", "energizing", "brightness", "warmth", "connection to the outside", "sense of time/season", "view", "uniform", and "diffuse", were overwhelmingly selected by participants. Many of these concepts can only be provided by daylight, not artificial light, which makes designing for daylight crucial.

These results clearly illustrate the shortcomings of current daylight metrics in assessing the qualitative aspects of daylight and underlines the need for a standardized list of daylight descriptors that can be used among researchers to understand the effect of daylight distribution on users' perception and satisfaction. Current metrics and methods focus on light availability for task purposes while preventing discomfort "glare", but disregard more than 90% of the concepts that are perceived as important by humans, characteristics that are impacted by daylight and are desired by users.

Developing lighting metrics that encompass a more holistic view on the effect of light on users' perception of a space will require a multi-disciplinary approach. Because we spend so much time in them (Evans & McCoy, 1998), the quality of our interior spaces is vital; it is worth revisiting and reinvigorating our lighting design criteria and measurement metrics to inform and enable more user-friendly design.

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# Section 3- The Impact of Color and Simulation Detail on Subjective Impressions of Rendered Scenes in Immersive Virtual Reality [2]


## Abstract

This experimental study investigates the influence of simulation choices on participants' subjective impressions of a space in virtual reality (VR). Although the impact of simulation choices, such as the use of color and level of detail in a scene, has been investigated in terms of representational accuracy, little is known about their influence on people's appraisal of the scene. Thus, this experimental study aims to address this gap in knowledge and offer a starting point for understanding how the use of color and level of detail in virtual scenes can impact participants' subjective impressions. The results of this study facilitate greater intentionality and understanding in the selection of the simulation choices in subjective studies.

A total of 100 participants rated a typical office space with six different building skin patterns while immersed in a scene of the space wearing an Oculus Go VR headset. The scenes were rendered in three color variations (grayscale, partly colored using default DIVA-for-Rhino materials, and fully colored), and two variations of simulation detail (furnished and unfurnished scene). Each participant viewed six randomized scenes and evaluated perceptual attributes


[2] The content of this section is based on a paper in preparation for publication. This work is in collaboration with Dr. Kynthia Chamilothori as the second author. The text is reproduced here with the agreement of the co-author.

commonly used in lighting research (rating how pleasant, exciting, interesting, calming, and complex they found the space) as well as their satisfaction with the brightness and the view access in the space. The results demonstrate a significant effect of both color and level of detail on participants' overall evaluation of the space and highlight the importance of considering these simulation choices in experimental studies using simulated visual stimuli.

### 4-3.1 Introduction

Lighting simulations have been widely used in studies investigating the effect of lighting on building performance and occupant perception. The outcomes of these simulations are affected by a series of user choices in relation to the choice of materials, the level of detail included in the model, and the modelling of the surrounding environment, as well as the parameters selected to simulate and render the scenes (G. Ward & Shakespeare, 2004). Although considerable research has been devoted to investigating the impact of simulation parameters, such as the choice of materials and the level of detail, on representational accuracy (E Brembilla, Hopfe, & Mardaljevic, 2018; Eleonora Brembilla, Drosou, & Mardaljevic, 2016), we have a limited understanding of how adjusting these parameters affects the visual impressions of an immersive virtual environment.

Research on the effect of color and level of detail is progressing using real environments. However, the use of simulation technology to more efficiently investigate visual perception has not been used to advance our knowledge about the influence of color and furniture on participants' subjective impressions. Due to the advancement in technology, recent studies with simulated visual stimuli can efficiently test a greater diversity of choices in terms of level of detail and the presence of color in the scene, ranging from achromatic scenes with no furniture (Franz, Von Der Heyde, & Bülthoff, 2005; Rockcastle, Amunddadottir, & Andersen, 2016;

Rockcastle, Chamilothori, & Andersen, 2017) to mainly achromatic scenes with furniture (K. Chamilothori et al., 2019; Omidfar, Niermann, & Groat, 2015), and scenes with colored textures and furniture (Cauwert, 2013; Heydarian et al., 2015; Murdoch, Stokkermans, & Lambooij, 2015; Tantanatewin & Inkarojrit, 2016).

Existing studies using real environments or two-dimensional images have highlighted the importance of both color and furniture for perception. The presence of color has been shown to influence people's appraisal of a space (Hidayetoglu, Yildirim, & Akalin, 2012) as well as their performance (Stone, 2003) and attention (Camgöz, Yener, & Güvenç, 2004) while within it. In particular, the presence of color has led to office environments being evaluated as more pleasant and attractive (Öztürk, Yilmazer, & Ural, 2012), and to an improvement in workers' mood (Küller et al., 2006). In the same vein, research on the effect of furniture on participants' perception indicate a significant influence on how participants perceive the dimensions of a space (Von Castell, Oberfeld, & Hecht, 2014). The presence of colored objects (in this study, flowers and fruit) was also shown to lead to an increase in how pleasant, comfortable, stimulating, and bright a space is perceived to be (Boyce & Cuttle, 1990).

In terms of experimental methods for investigating the user's perception of luminous conditions, two-dimensional visualizations have been suggested as a promising medium (Kuliga, Thrash, Dalton, & Hölscher, 2015; Mahdavi & Eissa, 2002; Murdoch et al., 2015). However, impressions of specific attributes, such as pleasantness and brightness, can differ significantly from those in a real environment (Cauwert, 2013). The use of immersive virtual reality has been proposed as an alternative experimental tool and has been shown to be an adequate surrogate for experiments investigating daylight perception in real spaces (Kynthia Chamilothori, Wienold, & Andersen, 2018a). Studies investigating the perceptual accuracy of simulated environments highlight the lack of knowledge regarding the impact of simulation materials and level of detail on perception (Kuliga et al., 2015; Mahdavi & Eissa, 2002; Murdoch et al., 2015). As the use of VR in research where the value of human response is valued is growing in popularity, it is essential to examine the effect of such simulation choices on participants' visual impressions to provide a support for future studies.

In this paper, we build upon an existing workflow for the generation of immersive scenes using Radiance (Kynthia Chamilothori, Wienold, et al., 2018a) software, used in this work to create omnidirectional stereoscopic projections of a typical office and investigate the effect of colored materials and the presence of furniture on participant perception through an experimental study in immersive virtual reality.

## 4-3.2 Methods

### 4-3.2.1 Visual Stimuli

Six variations of a typical office space with a large window facing south were modelled in Rhinoceros 5 to create the visual stimuli for this experimental study. In each variation, a different building skin pattern was applied to the exterior of the window. These skin patterns originate from studies on the intuition of architects regarding the perceptual qualities of facades with different openings, and were selected based on the consensus of architects on the potential effect of these facade variations on perception (Kynthia Chamilothori, Wienold, & Andersen, 2018b). All skin patterns are based on existing buildings (Figure 4.3.1) but slightly modified to have a 40% opening ratio. The 40% perforation ratio was selected as it has been shown as one of the most preferred solid-to-void ratios in previous studies on aesthetic preference (Kynthia Chamilothori, 2019; Friedenberg & Liby, 2016), and in order to maintain the level of brightness across all variations. The geometry of the skin patterns varied from simple horizontal louvers to complex irregular patterns (Figure 4.3.1).

The models were exported to the Radiance simulation tool (G. J. Ward, 1994) using the DIVA-for-Rhino toolbar (Jakubiec & Reinhart, 2011). To render the scenes, a view position in the center of the room was set at approximately 2.5 meters from the window and 1.63 meters from the floor, corresponding to the eye height of a standing person. A total of 30 office scenes were developed from permutations involving six skin patterns, presence or absence of furniture, and three color modes—grayscale, partly colored using default materials in DIVA, and fully colored—as shown in Figure 4.3.3. To reduce the number of immersive scenes, partly colored images without furniture were eliminated, as they were similar to the grayscale images. These scenes were simulated in Radiance using the view360stereo.cal script, resulting in a 360° over-under equirectangular high dynamic range (HDR) image for each scene variation. The simulation parameters used in Radiance are provided in Table 4.3.1.

The resulting HDR images were tone-mapped to a low dynamic range using the Reinhard02 tone-mapping operator (Reinhard, Stark, Shirley, & Ferwerda, 2002) and transformed to PNG files using the pfstools package. The final images were shown to participants using the Oculus GO virtual reality headset, and were perceived as a fully immersive 360° stereoscopic environment, as illustrated in Figure 4.3.2.

*Table 4.3.1: Radiance simulation parameters*

| **dj** | **ds** | **dt** | **dc** | **dp** | **St** | **ab** | **aa** | **ar** | **ad** | **as** | **lr** | **lw** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.02 | 0.05 | 0.05 | 0.5 | 256 | 0.5 | 4 | 0.02 | 32 | 25000 | 12500 | 4 | 0.000004 |

dj= source jitter, ds=source substructuring, dt= direct thresholding, dc= direct certainty, dp= direct pretest density, st= specular threshold, ab= ambient bounces, aa= ambient accuracy, ar= ambient resolution, ad= ambient divisions, as= ambient super-samples, lr= limit reflection, lw= limit weight.

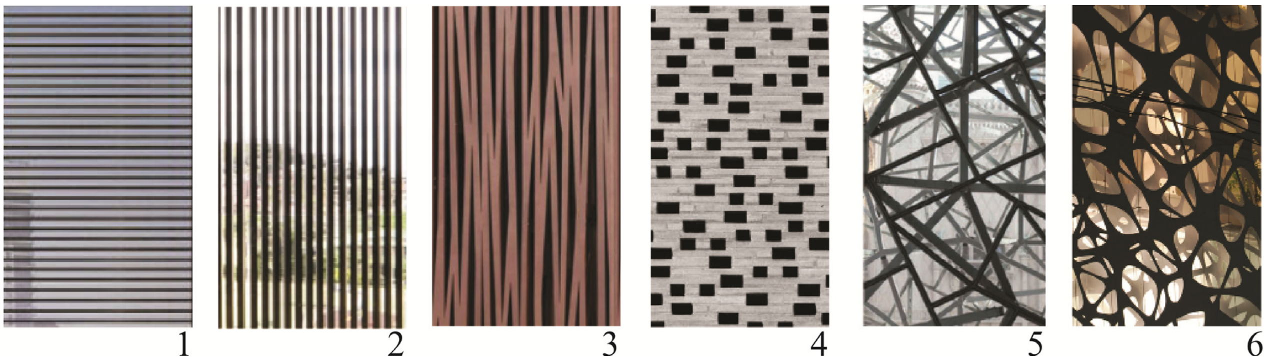


*Figure 4.3.1: Origin of six skin patterns, from left to right:[1] Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012; [2] Freshwater House, Chenchow Little, Sydney, Australia, 2008; [3] Selcuk Ecza Headquarters, Tabanlıoglu Architects, Istanbul, Turkey, 2013; [4] Kew House, Piercy & Company, Richmond, United Kingdom, 2014; [5] Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002; [6] Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

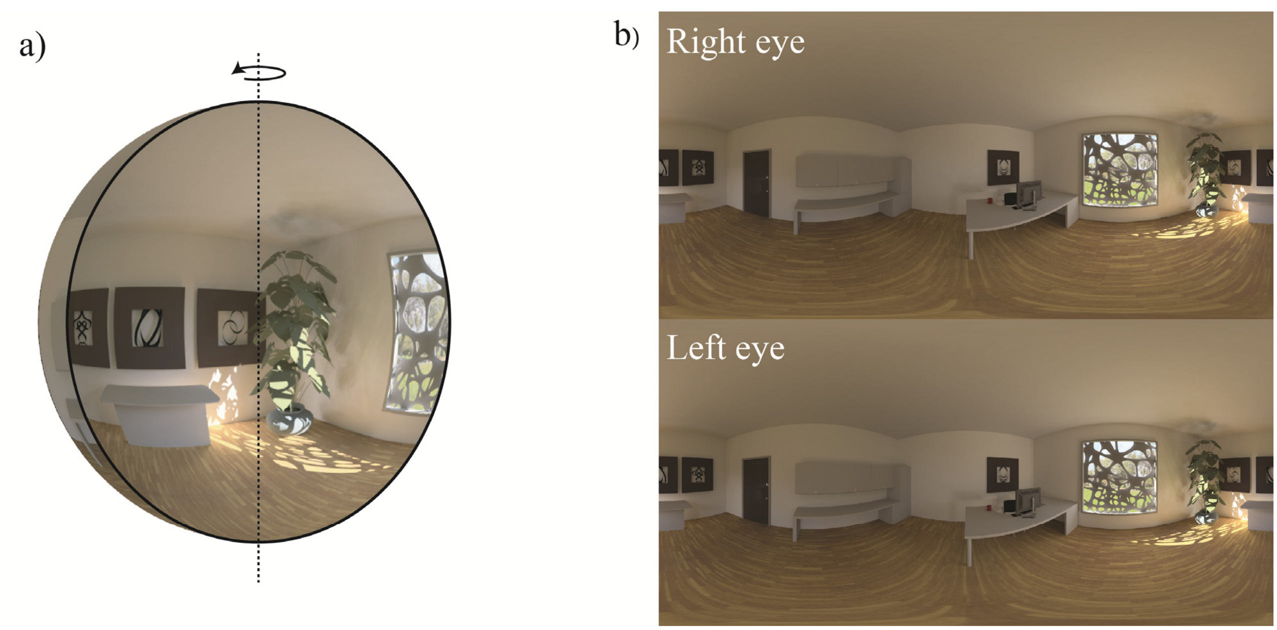


*Figure 4.3.2: Illustration of the immersive scene (a) and the 360° over-under stereo equirectangular projection to create the immersive scene (b).*

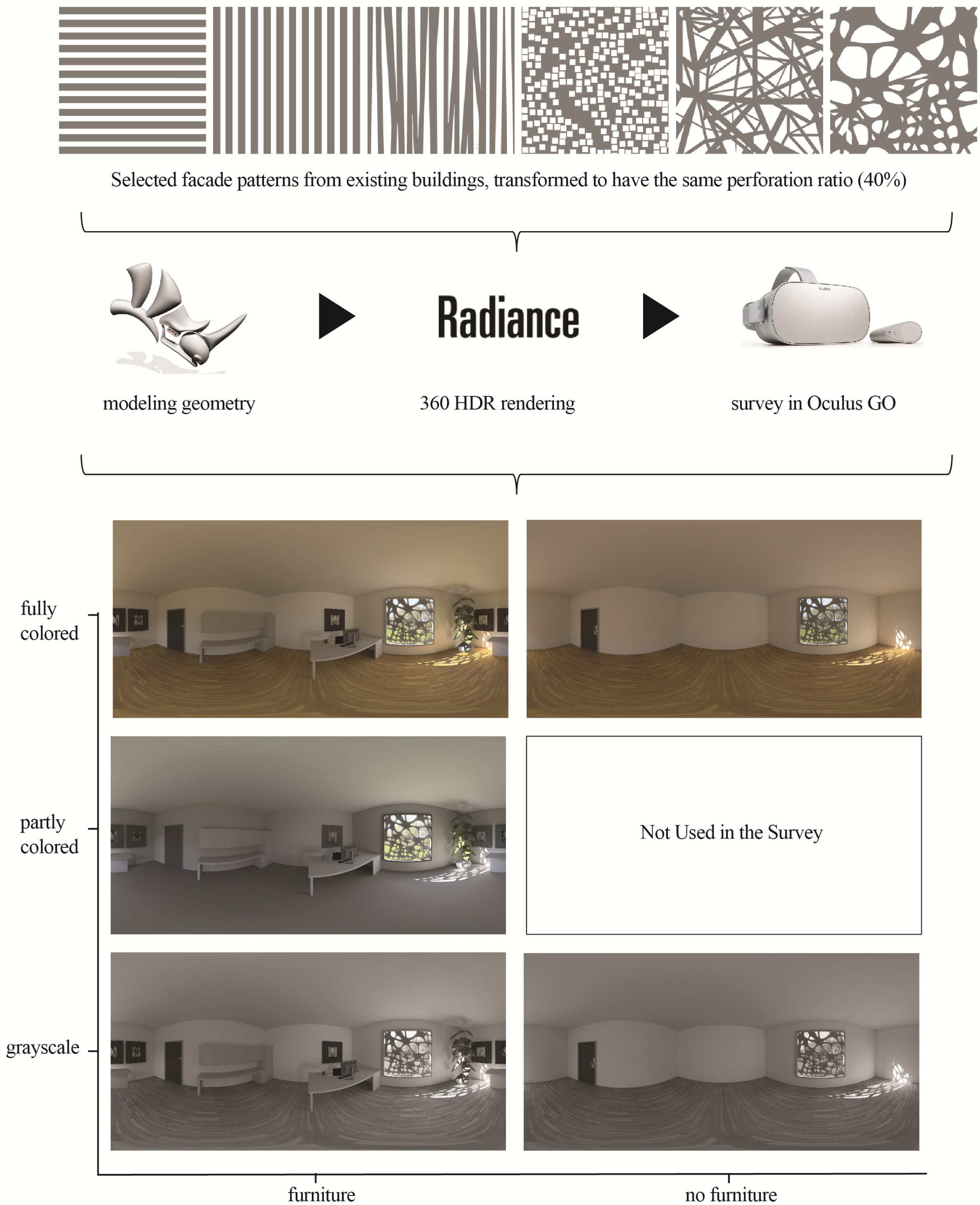


*Figure 4.3.3: Illustration of the simulation workflow and examples of the resulting scene variations used in the experimental study.*

4-3.2.2 Verbal Questionnaire

The verbal questionnaire for this experimental study consisted of 11-point unipolar rating scales ranging from 0 (not at all) to 10 (highly) and was used to assess participants' perception, emotional reactions and satisfaction during their immersion in each scene. In this paper, we focus on the effect of color and level of detail on the attributes listed in Table 4.3.2. These attributes relate to the atmosphere of the environment (how pleasant, exciting, interesting, and calming is the space), to the visual complexity of the environment, and to the participants' satisfaction with the scene's brightness and the amount of view to the exterior.

*Table 4.3.2: Overview of variables and questionnaire items*

| |
|---|
| **Independent Variables** |
| IV1. Building skin pattern variations (six different skin patterns of an equal perforation ratio applied to the window of the office room) |
| IV2. Scene color (gray, partly colored with default materials in DIVA-for-Rhino, fully colored) |
| IV3. Level of detail (simple room without furniture, simple room with furniture) |
| **Dependent Variables** (where 0 = not at all and 10 = highly) |
| DV1. On a scale of 0 to 10, how pleasant is this space? |
| DV2. On a scale of 0 to 10, how exciting is this space? |
| DV3. On a scale of 0 to 10, how interesting is this space? |
| DV4. On a scale of 0 to 10, how calming is this space? |
| DV5. On a scale of 0 to 10, how complex is this space? |
| DV6. On a scale of 0 to 10, how satisfied are you with the brightness of the space? |
| DV7. On a scale of 0 to 10, how satisfied are you with how much you can see of the view outside? |

#### 4-3.2.3 Equipment

The participants in this study were immersed in the scenes by wearing an Oculus Go VR headset. The headset's display has a Wide Quad High Definition (WQHD) resolution of 2560x1440 pixels, with a maximum refresh rate of 72 Hz. The Oculus Go is a standalone VR headset, which unlike Oculus Rift, does not require connection to a computer, and the resulting mobility led to its selection for this study.

#### 4-3.2.4 Participants and Experimental Design

The experimental study was conducted in Ann Arbor, Michigan over the course of four weeks in 2018. Each session lasted a maximum of 20 minutes. A total of 100 subjects (63 women, 37 men) participated. Participants were unpaid volunteers over 18 years of age, recruited by email or in person. Prior to the start of the session, the researcher discussed with the participant the possible risk associated with wearing the headset. Participants were also instructed on using the Oculus Go headset and adjusting its fit as needed. The study was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (IRB-HSBS, Case Number: HUM00147858).

Each participant was presented with a total of six scenes in a randomized order, of the 30 possible scenes that varied in skin patterns, color mode and furniture. The randomized scenes were preceded by a number identifying the scene condition to the researcher. When the participants were ready to begin the experiment, they were informed about the total number of the scenes they were going to view, and they were instructed to report the number associated with each scene. The researcher then verbally asked the questions in a randomized order regarding the presented scene, while the participant was immersed in the virtual environment.

#### 4-3.2.5 Statistical Analysis

A linear mixed effects model was used for statistical analysis of the data to account for the repeated measures as each participant viewed and rated multiple images. The rendering types (color, grayscale and default materials) and furniture were added as fixed effects, and the participant number as well as the skin patterns were specified as random factors. The statistical analysis of the data was conducted using the R statistical software (Team, 2018) and the lmerTest R package was used to examine the effect of color and furniture on each attribute through linear mixed model analyses (Kuznetsova, Brockhoff, & Christensen, 2017). To account for the multiple comparisons in this study, a Bonferroni correction method was used. A Bonferroni correction is a type of statistical analysis used during multiple comparison testing to limit the chances of obtaining false positive (Bland & Altman, 1995). To perform the Bonferroni correction the original p value (0.05) is divided by the tests being performed. In this study, a Bonferroni-corrected significance level of 0.05/14 =0.0035[3] was used.

### 4-3.3 Results

#### 4-3.3.1 Effects of color on participant perception of and response to office scenes

The linear mixed model analysis of the results indicates that the participants' subjective impressions were significantly affected by color in the virtual scene. In particular, the scenes with color (color and partly colored scenes) had a statistically significant effect on the participants' evaluations of how pleasant ($F(2, 600) = 51.10$, $p<0.001$), exciting ($F(2, 600) = 46.1$, $p<0.001$), interesting ($F(2, 600) = 16.90$, $p<0.001$), and calming ($F(2, 600) = 16.78$, $p<0.001$) they rated the presented scene. The participants' level of satisfaction with the

[3] The results are reported with two degrees-of-freedom values. First reports the between-groups degrees of freedom, the second value reports the within-groups degrees of freedom (separated by a comma), followed by the F statistic and the significance level.

brightness in the space, as well as their level of satisfaction with how much they could see outside were also significantly influenced by the use of color in the scene (satisfaction with brightness: $F(2,600) = 73.33$, $p<0.001$, satisfaction with the amount of view out: $F(2,600) = 33.69$, $p<0.001$. However, the effect of color was not statistically significant for the participants' perception of scene complexity ($F(2,600) = 7.08$, $p=0.008$).

The difference between the participants' responses and the overall effect of fully colored, partly colored and grayscale scenes on the evaluations of each perceptual attribute can be seen in Figure 4.3.4.

The attributes of the scenes with color and partly colored materials are evaluated more positively then those with grayscale (Figure 4.3.4). With the exception of Calming, all grayscale scenes led to more negative evaluations compared to colored scenes, a result in agreement with findings in the literature (Küller et al., 2006; Öztürk et al., 2012). Table 4.3.3 provides a summary of the results of this subsection.

*Table 4.3.3: Summary of the effects of color on participants' subjective impressions of the scenes*

| | | | |
|---|---|---|---|
| Pleasant: | $F(2, 600) = 51.10$, $p<0.001$ | satisfaction with brightness: | $F(2,600) = 73.33$, $p<0.001$ |
| Exciting: | $F(2, 600) = 46.1$, $p<0.001$ | Satisfaction with the amount of view out: | $F(2,600) = 33.69$, $p<0.001$ |
| Interesting: | $F(2, 600) = 16.90$, $p<0.001$ | Complexity: | $F(2,600) = 7.08$, $p=0.008$ |
| Calming: | $F(2, 600) = 16.78$, $p<0.001$ | | |

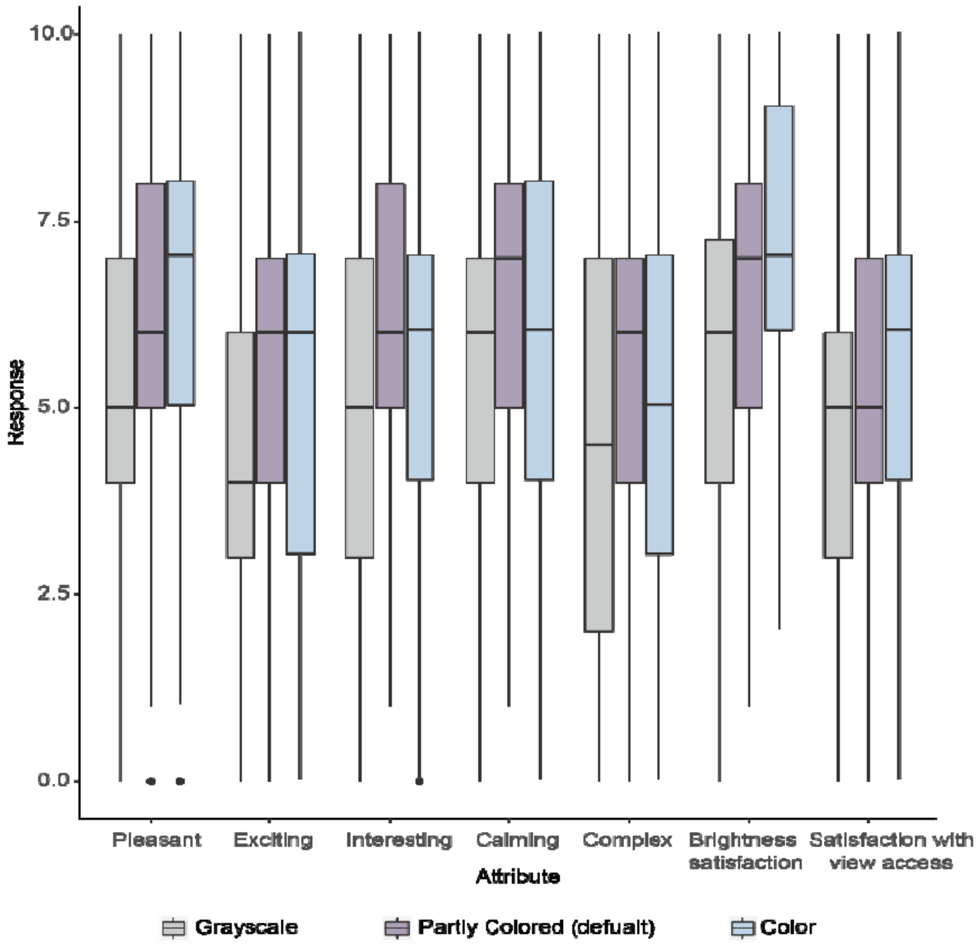


*Figure 4.3.4: Effect of color on the participants' responses across the studied attributes*

4-3.3.2 Effect of level of detail on participants' subjective impressions

The presence of furniture in the scene had a statistically significant effect on participants' responses regarding how pleasant ($F(1,601) = 45.69$, $p<0.001$), exciting ($F(1,601) = 124.98$, $p<0.001$), interesting ($F(1,601) = 162,45$, $p<0.001$) and calming ($F(1,601) = 18.59$, $p<0.001$) they found the space. Similarly, participants' evaluations of how complex the space was perceived were significantly influenced by the presence of furniture ($F(1,601) = 228.66$, $p<0.001$). The effect of furniture was not statistically significant for the evaluations regarding the satisfaction with brightness ($F(1,601) = 4.80$, $p=0.028$) or the satisfaction with view access in the space ($F(1,601) = 2.55$, $p=0.11$).

The influence of furniture on the participants' subjective impressions is illustrated in Figure 4.3.5, illustrating a more positive evaluations for all attributes that were significantly influenced by the presence of furniture in the scene. Table 4.3.4 provides a summary of the results in this subsection.

*Table 4.3.4: Summary of the effect of level of detail on participants' subjective impressions*

| | | | |
|---|---|---|---|
| Pleasant: | (F(1,601) = 45.69, p<0.001 | satisfaction with brightness: | F(1,601) = 4.80, p=0.028 |
| Exciting: | F(1,601) = 124.98, p<0.001 | Satisfaction with the amount of view out: | F(1,601) = 2.55, p=0.11 |
| Interesting: | F(1,601) = 162,45, p<0.001 | Complexity: | F(1,601) = 228.66, p<0.001 |
| Calming: | F(1,601) = 18.59, p<0.001 | | |

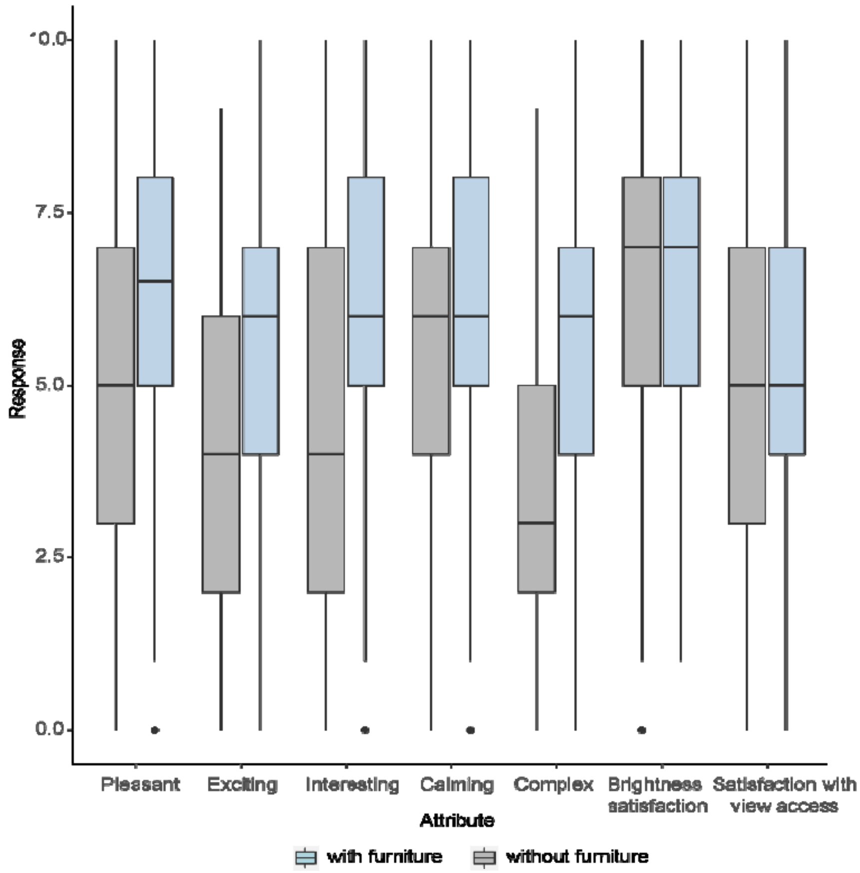


*Figure 4.3.5:* Effect of furniture on the participants' responses across the studied attributes

### 4-3.4 Summary

This section introduced an experimental study on the effect of color and furniture on participants' subjective impressions using immersive 360° scenes of an office environment shown in the Oculus Go VR headset. The scenes were rendered in grayscale, partly colored and fully colored materials, and were randomly presented to participants with and without furniture. Participants' subjective impressions of each scene were collected using a verbal questionnaire. The results demonstrate a significant positive influence of color in the scene (vs. grayscale) on the evaluations of how pleasant, exciting, and calming the space was perceived to be. Moreover, the use of color led to participant reports of higher levels of satisfaction with the brightness in the space and their perception of how much they could see outside. Specifically, full color yielded more positive perceptions than partial color, and partial color was more favorably perceived than grayscale scenes. The only exception was how calming the spaces were perceived, for which partly colored scenes were most positively evaluated.

The level of detail in the scene significantly affected how pleasant, exciting, interesting, calming, and complex participants rated the presented scenes. For these attributes, the presence of furniture in the scene led to more positive evaluations. These results signify that the level of detail in scenes that are used as stimuli in studies investigating the participants' impressions of interior spaces is an important factor to consider, as the presence of furniture can influence the participants' responses.

These findings have important implications for research investigating people's impressions of simulated environments, as they demonstrate the impact of choices in the simulation process on the judgment of commonly evaluated attributes, such as the brightness and pleasantness of the scene. Although the presence of colors, textures, and furniture add a layer of complexity to the simulation process and could be computationally expensive, it is important to understand how these factors may impact the participants' evaluations of various environments, and thus become a critical choice in the design of experimental studies with simulated visual stimuli. This study not only highlights the perceptual attributes that were influenced by the presence of color and furniture in the scene, such as how pleasant a space is perceived to be, but also those that were not affected by these simulation factors. In this regard, the findings of the present study could be used to orient future work regarding the choice of color and level of detail in the simulation process, depending on the attributes under investigation.

VR technology has been used in field of architecture as a tool to engage with clients, to allow them to explore and react to the virtual space. It has also been used in the field of architectural and lighting research as a way of evaluating the effect of spaces on participants' physiological and psychological responses (Kynthia Chamilothori, Chinazzo, et al., 2018). Architects, interior architects, designers and lighting designers create and shape the spaces that people use—they design for people, creating environments that have strong effects on occupants' physical and emotional wellbeing. Thus, it is critical for designers to have appropriate information about the attributes that impact the subjective impression of occupants. The outcome of this research will guide design professionals and researchers in their selection of simulation choices when creating virtual scenes for an immersive experience.

## 4-3.5 References


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# Section 4- Subjective Impressions of a Space Influence Brightness Satisfaction: An Experimental Study in Virtual Reality[4]


## Abstract

The term "brightness" in lighting design can refer either to subjective assessment or photometric quantity (Cuttle, 2017). The relationship between photometric quantity and the subjective assessment of that quantity has not yet been fully studied. This experimental study investigates the relationship between participants' satisfaction with brightness and other key perceptual attributes of the scene to gain insight in how user satisfaction with brightness is influenced by factors other than brightness levels. In this study, a total of 100 participants were immersed in an office space using virtual reality (VR). The brightness levels in all immersive scenes were held constant while the design pattern of the office building skin, rendering materials, and furniture were varied to examine how factors other than brightness influence the participants' satisfaction with brightness itself. Statistical analyses indicate that there is a strong association between participants' satisfaction with brightness and other perceptual attributes such as access to the view outside, perceived pleasantness, interest, complexity and the overall ambiance. Additionally, while the effect of furniture on brightness satisfaction was not statisticallysignificant, the analyses revealed that colored materials had a significant effect on participants' evaluations of their satisfaction with brightness.


[4] The content of Chapter 4 Section 4 is based on a published article (A. O. Sawyer and K. Chamilothori, "Influence of Subjective Impressions of a Space on Brightness Satisfaction : an Experimental Study in Virtual Reality," in *Simulation for Architecture and Urban Design (SimAUD)*, 2019, no. April, p. 8.). Text from that article is reproduced here with the agreement of the co-author.

### 4-4.1 Introduction

*"…when people in workplaces equipped with modern, efficient lighting complain about the lighting, their objections are likely to be directed towards the appearance of their surroundings. They may find the appearance of the workplace to be dull or gloomy, or the effect of lighting to be harsh, producing dense and unattractive shadows."*

*Christopher Cuttle* (Cuttle, 2010)

Light has an undeniable influence on our perception of space, as recognized in the fields of architecture (Holl, Kwinter, & Safont-Tria, 2011; Pallasmaa, 2012; Zumthor, 2006) and of lighting (Flynn, Spencer, Martyniuk, & Hendrick, 1973; Hawkes, Loe, & Rowlands, 1979; Veitch & Newsham, 2000). The design of the luminous conditions in a space aims to address the needs of the occupants, and substantial research effort is devoted to identifying the characteristics of ideal lighting conditions for different social situations and for various tasks. In the case of work environments, lighting is used to ensure that workers can perform their tasks quickly, accurately and easily (Boyce, 2014).

In one study people were asked to freely describe the lighting in an office-like room and brightness was the second the most commonly used attribute (Boyce & Cuttle, 1990). Interestingly, the most commonly used description was that the lighting in the room was dull. Although this finding could be a result of the stimulus range used in the experiment, it raises the question of which features of the luminous environment matter most in occupants' perception. This question was tackled in a seminal study by Flynn and colleagues in which the appearance of a conference room was examined under different configurations of artificial lighting (Flynn et al., 1973). Their experiment showed that people prefer lit environments that appear 'bright', an attribute linked to the perception of 'spaciousness', and 'interesting', an attribute related to a degree of non-uniformity. They concluded that lighting conditions can be characterized by three dimensions: brightness, uniformity, and the presence of peripheral or overhead lighting. In another study with artificial lighting configurations in an office environment, Hawkes et al. found that the perception of light in the space could be described by the dimensions of brightness and interest, which related to the intensity and the uniformity of the lighting conditions, respectively (Hawkes et al., 1979). Similarly, Loe et al. identified the factors of visual lightness and visual interest as descriptors of the luminous environment, using the same procedure as Flynn (Loe, Mansfield, & Rowlands, 1994). The work of Loe et al. supported the findings of previous research regarding people's preference for their working environment to appear 'bright' and 'interesting', but also noted a key criterion for lighting design, stating that both factors are required to create preferred lighting conditions. That is, people do not prefer a 'bright' space if it is not 'interesting', or an 'interesting' space that is not 'bright'. In a later study by Veitch and Newsham on the appearance of an open-plan office lit with different lighting systems, the authors found three factors that described the appearance of the space: brightness, visual attraction, and complexity (Veitch, Jennifer a., Newsham, 1997). Brightness is a consistent factor across these studies, which establishes its importance as a central feature of the luminous environment.

Considerable research has been conducted to identify physical measures of the lighting conditions that can predict occupants' impressions of brightness. The perception of brightness in a space has been related to objective indicators such as the average luminance within a 40 degree horizontal band center at the eye height of an observer (Loe et al., 1994; Stokkermans, Vogels, de Kort, & Heynderickx, 2017), the logarithm of the vertical illuminance at the eye of the observer (Hawkes et al., 1979), and the spectrally-weighted irradiance at the eye of the observer (Rea, Mou, & Bullough, 2016).

In related work, numerous studies have investigated the influence of physical properties other than light intensity on the perceived brightness of a space. For instance, Tiller and Veitch investigated the effects of luminance distribution on perceived room brightness in office spaces using brightness matching tasks in offices. Their findings showed that rooms with non-uniform luminance distribution required five to ten percent less working plane illuminance compared to the brightness of the rooms with uniform luminance distribution (Tiller & Veitch, 1995). The spectrum of the light source has also been consistently shown to affect the perceived brightness of the scene (J. D. Bullough, Radetsky, Besenecker, & Rea, 2014; J. Bullough, Radetsky, & Rea, 2011; S. A. Fotios & Cheal, 2007; S. Fotios & Cheal, 2011). The presence of color in the scene in the form of colored objects (in this example, flowers and fruit) was also shown to increase the perception of brightness in the same illuminance (Boyce & Cuttle, 1990). However, other studies showed no or only a negligible effect from the presence of colored objects on the perceived brightness of the scene (J. Bullough et al., 2011; S. Fotios & Cheal, 2011), indicating the need for further investigation.

It is important to note here that a common component of all these studies is the use of artificial lighting. In fact, very few studies have addressed the effect of daylight on occupants' preference and satisfaction. However, sunlight penetration has been shown to increase feelings of relaxation (Mohamed Boubekri, Hull, & Boyer, 1991) as well as well-being and job satisfaction (M. Boubekri & Boyer, 1992). In the same vein, in an experimental study that asked occupants of office environments to control the shading system and create their preferred conditions, the majority of the participants chose to introduce some amount of direct sunlight into the room (Van Den Wymelenberg, Inanici, & Johnson, 2010). Studies investigating the effect of daylight on participants' subjective impressions in virtual environments have shown that the lighting conditions significantly influence the extent to which a space is perceived as pleasant, interesting, and exciting (Chamilothori, Wienold, & Andersen, 2016; S. Rockcastle, Amundadottir, & Andersen, 2017; Siobhan Rockcastle, Chamilothori, & Andersen, 2017). Following these findings, a question arises: could occupants' perception and satisfaction with brightness be affected by other perceptual attributes of the space rather than just the actual brightness level of the space? Such a finding could suggest the potential for energy savings if the same level of satisfaction with brightness can be achieved at lower actual levels of illuminance by manipulating other attributes of the luminous environment.

This paper investigates the influence of perceptual attributes—such as the perceived pleasantness or complexity of the scene—on occupants' satisfaction with the brightness in a daylit office space through subjective experiments. The visual stimuli in these experiments are shown to the participants using a novel experimental method which combines physically-based renderings from Radiance with projection in immersive virtual reality, and has been shown to be a promising surrogate to real daylit spaces for experiments investigating occupant perception (Chamilothori, Wienold, & Andersen, 2018). Specifically, this study comparing subject perceptions in VR versus real environments demonstrated the adequacy of VR and reported no significant differences between the virtual and real environments (Chamilothori et al., 2018). The use of virtual reality allows brightness to be controlled and kept at same level across multiple scenes. At the same time, VR allows multiple variations of a building skin design to be applied to the same space, creating different impressions of visual interest and complexity. In this study, controlling the brightness level of the scene across conditions that trigger widely different perceptual impressions allowed us to examine the interrelationship between satisfaction with brightness and other key attributes related to office preference attributes, such as access to the view outside, perceived pleasantness, interest, complexity, and overall ambiance. Additionally, the presence of color and furniture in the virtual environment was varied to investigate the influence of these factors on participants' satisfaction with brightness.

## 4-4.2 Method

This experiment uses the same experimental approach described in Chapter 4 Section 3 but builds upon it by carrying out a deep investigation of participants' objective and subjective evaluation of brightness. The following section describes the method used to conduct this experimental research study. It has five aspects: the visual stimuli, verbal questionnaire, equipment, experimental design and participants, and statistical analysis.

### 4-4.2.1 Visual stimuli

The scenes used as visual stimuli in this experimental study correspond to six variations of a typical office space with one large window facing south. In these variations, developed in previous work (Chamilothori et al., 2018), a different building skin design was applied to the facade of the space, shown in Figure 4.4.1. Each skin variation was based on designs from existing buildings, ranging from simple vertical or horizontal louvers to an asymmetrical complex pattern (Figure 4.4.1). These variations of the scenes were used to impart different subjective impressions, following existing work which demonstrated the influence of building skin geometry on occupant perception (Chamilothori, Wienold, & Anderson, 2016; Omidfar, Niermann, & Groat, 2015). Although the building skins varied in design, all were modified to have 40% perforation in order to create scenes with the same amount of brightness and with distinct perceptual attributes. A 3D model of the office space with six building skin variations was created in Rhinoceros (Rhino, version 5.0) modelling software. Six different spaces were modeled both with and without furniture. Each was rendered in three different color modes—

fully colored, partly colored (using the default materials in DIVA-for-Rhino v. 4.0), and grayscale (Figure 4.4.2). A view position in the center of the room was established at approximately 2.5 meters from the window and 1.63 meters from the floor, corresponding to the eye height of a standing person. Each model was exported to Radiance (Ward Larson & Shakespeare, 1998), an extensively validated physically based lighting simulation tool, using the DIVA-for-Rhino (v. 4.0) simulation toolbar (DIVA-for-Rhino, 2018). Immersive scenes were generated in Radiance by rendering a 360° over-under equirectangular HDR image using the script *view360stereo.*cal.

The parameters for the Radiance simulation are provided in Table 4.4.1. This procedure resulted in a total of 30 images, which were tone-mapped to a low dynamic range using the Reinhart02 tone-mapping operator (Reinhard, Stark, Shirley, & Ferwerda, 2002) and shown to participants using the Oculus Go virtual reality headset. The resulting scenes are automatically mapped to a sphere in Oculus Go and are perceived as a fully immersive 360° stereoscopic scene (Figure 4.4.3). The vertical illuminance of the projected scenes was measured at the level of the lens of the VR headset with a Konica Minolta T-10 Illuminance Meter from the viewpoint of a participant looking towards the main view direction, to provide a measure of similarity in terms of actual brightness. These measurements show that the studied scenes differ between them in vertical illuminance with a maximum factor of 1.13, which is well below the threshold of a noticeable change in illuminance (European Committee for Standardization, 2002), and thus is not expected to result in a difference in the participants' judgments regarding their satisfaction with the brightness of the space.

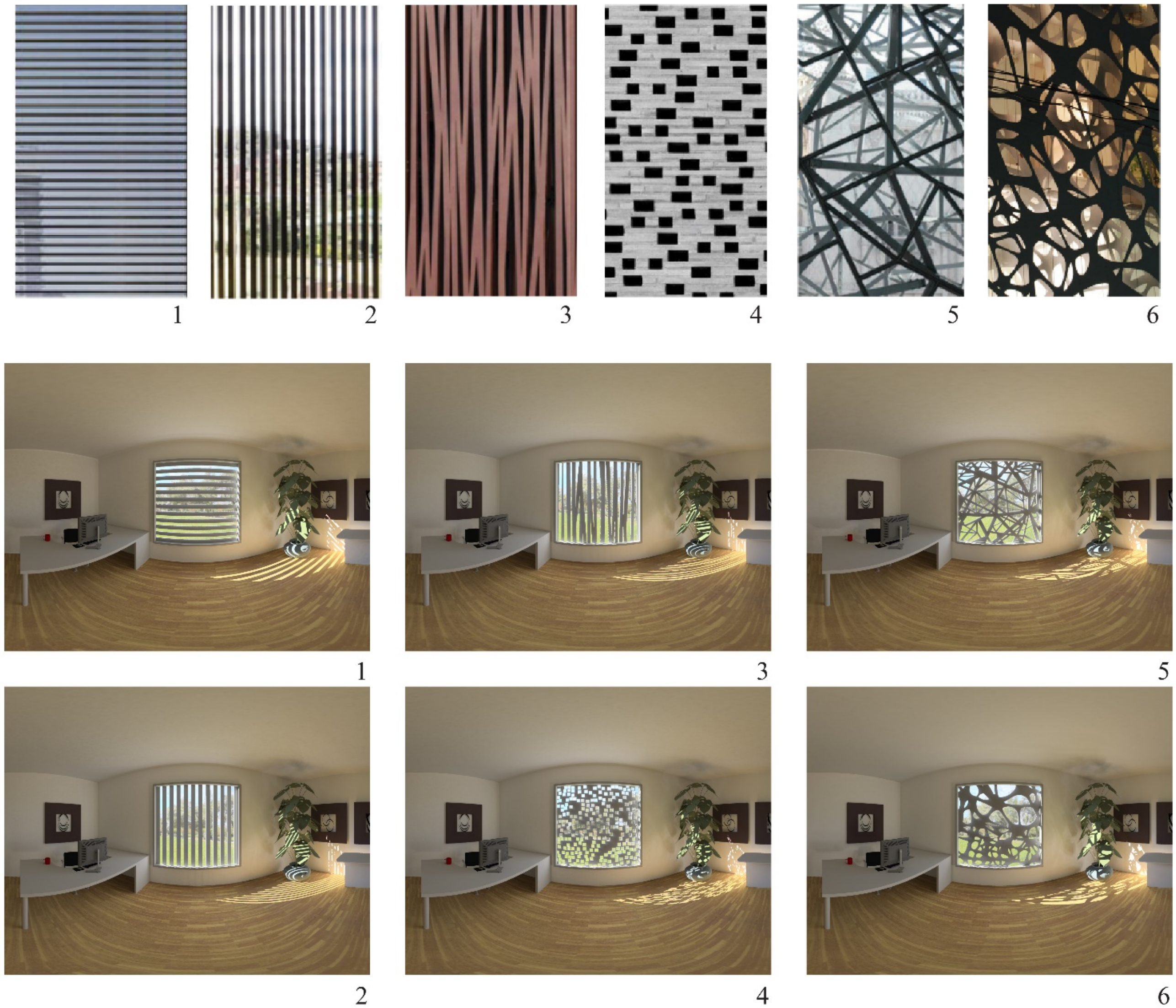


*Figure 4.4.1: From left to right:[1] Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012; [2] Freshwater House, Chenchow Little, Sydney, Australia, 2008; [3] Selcuk Ecza Headquarters, Tabanlıoglu Architects, Istanbul, Turkey, 2013; [4] Kew House, Piercy & Company, Richmond, United Kingdom, 2014; [5] Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002; [6] Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007*


*Figure 4.4.2. Example scene variations for one building skin design across different levels of scene colors (fully colored, partially colored, grayscale) and simulation level of detail (with/without furniture). Each participant saw a random selection of scenes.*

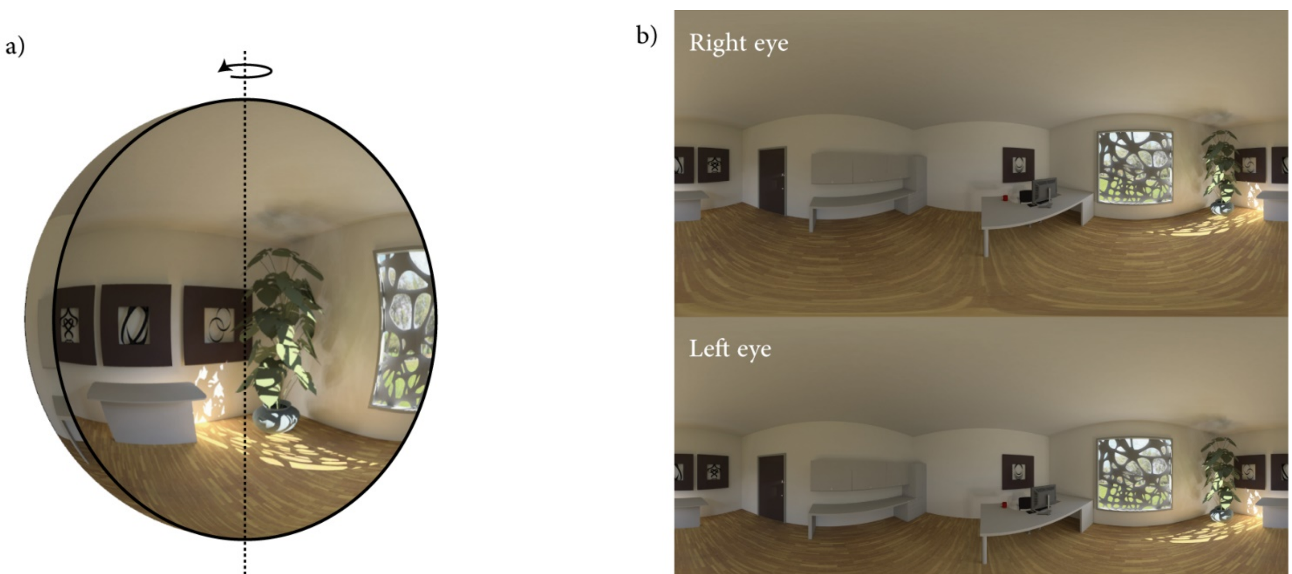


*Figure 4.4.3. Illustration of the immersive scene (at) and the 360° over-under stereo equirectangular projection to create the immersive scene (b)*

*Table 4.4.1: Radiance parameters for the 360° HDR renderings for viewing in Oculus Go.*

| dj | ds | dt | dc | dp | st | ab | aa | ar | ad | as | lr | lw |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.02 | 0.05 | 0.05 | 0.5 | 256 | 0.5 | 4 | 0.02 | 32 | 25000 | 12500 | 4 | 0.000004 |

*Key to abbreviations shown here can be found in Table 4.3.1*

4-4.2.2 Verbal Questionnaire

A verbal questionnaire consisting of 11-point unipolar rating scales was used to collect participants' subjective impressions while they were immersed in each scene. In this paper, we focus on the participants' satisfaction with brightness and its association with a selection of rating scales: how pleasant, interesting, and complex the scene was perceived, as well as their satisfaction with the view out and the ambiance of the space, shown in Table 4.4.2. It is important to note here that the question on brightness was specifically framed to assess the participants' satisfaction with brightness as an indicator for acceptable range of brightness rather than their perception of brightness levels.

*Table 4.4.2: Overview of the experimental variables*

**Independent Variables**

IV1. Building skin variations (six different building skins of an equal perforation ratio applied to the window of the office room).

IV2. Scene color (fully colored, partly colored (with default materials in DIVA-for-Rhino), and grayscale.

IV3. Level of detail (simple room without furniture, simple room with furniture).

**Dependent Variables (**where 0 = not at all and 10 = highly)

DV1. On a scale of 0 to 10, how pleasant is this space?

DV2. On a scale of 0 to 10, how interesting is this space?

DV3. On a scale of 0 to 10, how complex is this space?

DV4. On a scale of 0 to 10, how satisfied are you with the brightness of the space?

DV5. On a scale of 0 to 10, how satisfied are you with how much you can see of the view outside?

DV6. On a scale of 0 to 10, how satisfied are you with the ambiance of the space?

#### 4-4.2.3 Equipment

An Oculus Go VR headset was used in this study. This is a standalone headset that works without a computer or a phone. Its screen measures 5.5 inches, 538 ppi, at 2560 x 1440 Wide Quad High Definition (WQHD) resolution. The display can run at a maximum refresh rate of 72 Hz, delivering enhanced brightness and colors. The maximum vertical illuminance of a white scene displayed in Oculus Go measured at the level of the lens is 44 lux ($lm/m^2$).

#### 4-4.2.4 Experimental Design and Participants

Each participant was presented with a total of six scenes in a randomized order, from the pool of 30 combinations of building skin, color, and furniture variations. Due to the randomization of the scenes, not all participants viewed all six building skins used in the study. Analysis of the effect of the building skin design on subjective impressions exceeds the scope of this paper and will be reported in a future publication.

The VR experimental study was conducted in Ann Arbor, Michigan over the course of four weeks during the summer of 2018. A total of 100 participants (63 female, 37 male) took part in the study. Participants were unpaid volunteers over 18 years of age, recruited by email or in person. Each experimental session lasted no more than 20 minutes.

Prior to the start of the experimental session the interviewer discussed possible risks associated with wearing the headset with the participant. When they were ready to start the experiment, they were instructed on how to use the Oculus headset and how to customize its fit for comfort. Participant were informed that they would view a total of six scenes of an office space. The scenes were presented in a randomized order and were preceded by a number identifying the condition to the interviewer. Participants were instructed to report this number and were then immersed in an office scene. When the participant was ready, the interviewer verbally asked the questions in a randomized order.

This research was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (IRB-HSBS, Case Number: HUM00147858).

#### 4-4.2.5 Statistical analysis

A linear mixed effects model was used for statistical analysis of the data to account for the repeated measures design in which each participant was asked to rate multiple images. Model analyses were conducted in R (Team, 2018) for each of the dependent variables using the R software package *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017). The linear mixed effects model describes the conditional associations between the participants' satisfaction with brightness and the five other perceptual attributes, while controlling for latent participant attributes such as positivity. Statistical analyses were performed at a 0.05 significance level.

Additionally, following the results regarding the associations between the participants' satisfaction with brightness and the other studied dependent variables, a composite index of *satisfaction with selected attributes* was constructed in R by averaging the responses of the attributes *pleasant*, *interesting*, *satisfaction with access to the view outside*, and *satisfaction with ambiance*. This composite index is used to quantify a potential effect on satisfaction with brightness that could stem from a change in the participants' perception of these four attributes, rather than a change in the actual brightness of the scene.

### 4-4.3 Results

The following subsections present the results of the statistical analyses used to study the subjective responses related to the effect of color and furniture on participants' satisfaction with brightness, the associations between satisfaction with brightness and other perceptual attributes, and the comparison of satisfaction with brightness with a composite index of satisfaction with perceptual attributes in the space.

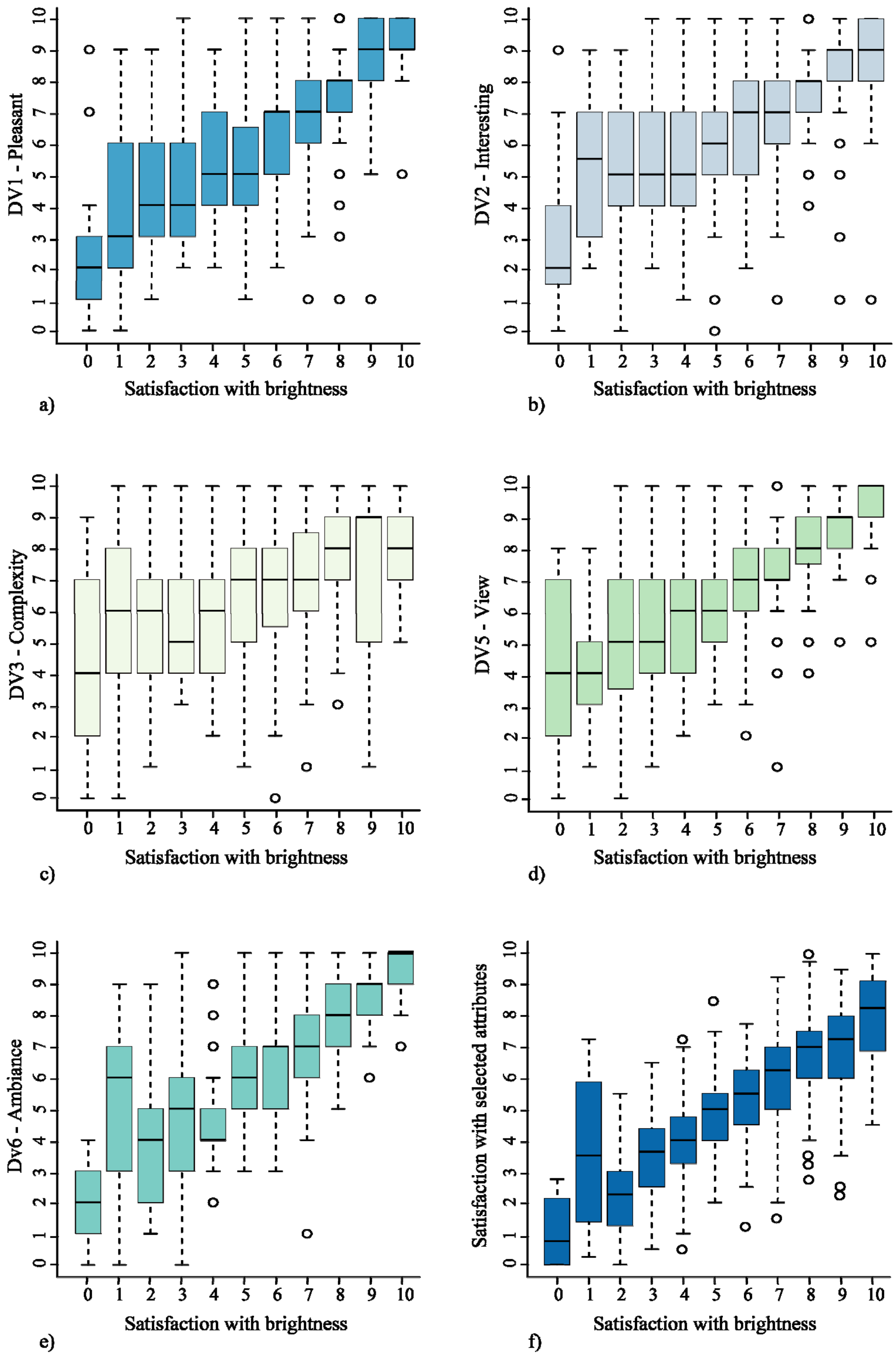


*Figure 4.4.4. (a)-(e) Boxplots of evaluations of participants' perceptual impressions of the space (y axis), plotted against the equivalent ratings of satisfaction with brightness (x axis), and (f) ratings of the composite index of satisfaction with selected attributes (y axis) plotted against the equivalent ratings of satisfaction with the brightness of the space (x axis).*

4-4.3.1 Influence of skin pattern, color and furniture on satisfaction with brightness

Although the actual brightness level of all scenes was the same, participants' evaluations of their satisfaction with brightness spanned the full range of the rating scale (0 to 10 units), with a mean of 6.1 and a standard deviation of 2.18. Linear mixed model analyses were conducted to investigate separately the effect of color and of furniture on the participants' responses. For these analyses, a Bonferroni-corrected significance level of $0.05/2 = 0.025$ is used to account for the multiple comparisons. Results show a statistically significant main effect of color ($F(2,600) = 75.33$, $p<0.001$) on participants' evaluations of their satisfaction with the brightness in the space. In particular, participants' satisfaction with brightness in the scenes with fully colored materials were on average 1.3 units higher than the ratings in the corresponding grayscale scenes. The effect of furniture was not statistically significant on participants' satisfaction with brightness ($F(1,601) = 4.80$, $p=0.028$).

Two linear mixed effects models predicting perceived brightness in terms of color and furnishing were used. Both models included subject random effects to account for systematic perceptual and rating differences among subjects, and skin pattern random effects to account for differences among the facade patterns. The skin pattern random effect explains the overall degree of difference in brightness ratings among the skin patterns in terms of a single variance parameter. If zero, there is no difference in perceived brightness among the skin patterns. Positive variance parameters indicate that greater variation in brightness perception is attributable to the skin patterns. Our second model also included fixed effects for five perceptual ratings (not including brightness). These are included as covariates to account for inter-subject differences in rating behavior that are not captured by the random subject effect. We argue that both models are valid, though they control for inter-subject variation in different ways. Regardless, the pattern variance parameter was small in both models (pattern variance / total unexplained variance = 0 and $<10^{-6}$ in the models without/with fixed effects for five non-brightness perceptual attributes, respectively). Table 4.4.3 provides a summary of the results in this subsection.

*Table 4.4.3: Summary of the influence of color, furniture and skin on participants' satisfaction with brightness*

| | Color | Furniture | Skin |
|---|---|---|---|
| Satisfaction with the brightness | $F(2,600) = 75.33$, $p<0.001$ | $F(1,601) = 4.80$, $p=0.028$ | pattern variance / total unexplained variance = 0 and $<10^{-6}$ |

4-4.3.2 Associations between satisfaction with brightness and subjective impressions of the space

Further analyses were performed to investigate the association between satisfaction with brightness and the perceptual impressions of other attributes examined in the study. Positive statistically significant associations were found between the evaluations of *satisfaction with brightness* and evaluations of how *pleasant* ($b=0.16$, $p<0.001$) and *complex* ($b=0.08$, $p<0.05$) the space is perceived, as well as with the ratings of the *satisfaction with access to the view outside* ($b=0.11$, $p<0.01$), and the *satisfaction with the ambiance of the space* ($b=0.24$, $p<0.001$). No statistically significant association was found between the *satisfaction with brightness* and how *interesting* the space was perceived ($b= -0.04$, $p=0.35$). These associations can be observed in the plots (a) to (e) in Figure 4.4.4, showing the distribution of participants' evaluations of the space plotted against the corresponding ratings of satisfaction with brightness. Table 4.4.4 provides a summary of the results in this subsection.

*Table 4.4.4: Summary of the associations between satisfaction with brightness and subjective impressions of the space*

| | | | |
|---|---|---|---|
| Pleasant | $b=0.16$, $p<0.001$ | Satisfaction with the ambiance of the space | $b=0.24$, $p<0.001$ |
| Complex | $b=0.08$, $p<0.05$ | Satisfaction with access to the view outside | $b=0.11$, $p<0.01$ |
| Interesting | $b= -0.04$, $p=0.35$ | | |

4-4.3.3 Composite index of satisfaction with brightness based on other perceptual attributes

Following the findings of positive statistically significant associations between brightness and other perceptual attributes, we constructed a composite index representing participants' *satisfaction with selected non-brightness attributes* (as described in Section 4-4.2.5) to understand its association with participants' perception of brightness. To visualize this index using unadjusted data, we constructed a box plot of satisfaction with brightness in terms of *satisfaction with selected non brightness attributes* (Figure 4.4.4f). This plot shows a strong positive relationship between these two attributes, suggesting a possible effect on satisfaction with brightness that could be due to the participants' satisfaction with the selected attributes in the composite index.

Additionally, a simple composite was formed by taking the equally weighted average of the selected non-brightness attributes—*pleasant, interesting, view, and ambiance*. Cronbach's alpha for the mean score was 0.87, indicating that most of the variation in these four attributes is captured through their mean score. We then used this mean score to predict perceived brightness, and found that for each unit difference in the mean score, perceived brightness differed by 0.65 units. This implies that perception of brightness can be substantially predicted by a univariate summary of other positively valenced attributes.

## 4-4.4 Discussion

This experimental study investigates the influence of key aspects of participants' perceptual impressions of a scene, such as the pleasantness, the satisfaction with the access to the view or the ambiance of the space, on ratings of satisfaction with the brightness of that scene. Through the use of an experimental method which couples physically based renderings with projection in virtual reality, a total of 100 participants were immersed in virtual scenes of an interior an office space with different building skin variations, colored materials and with or without furniture.

Although the studied scenes had similar illuminance levels, these findings demonstrate a significant effect of colored materials on the participants' satisfaction with brightness. While the addition of colored materials in virtual environments adds a layer of complexity in the simulation workflow, these results highlight the importance of colored materials in assessing user's satisfaction with the brightness in a scene.

At the end of each questionnaire, the participants spoke openly about each of the scenes, sharing their likes and dislikes, while the conversations were recorded. One of the components in the scene that the majority of the participants expressed interest in was the plant and the shadow patterns on the plant (Figure 4.4.5).

*Figure 4.4.5: An image of a participant during the VR interview on the left, and the scene observed in VR on the right. The participant spoke about his appreciation of the plant and shadow patterns on the wood floor while immersed in the scene.*

The word “plant” was used 113 times by participants who referred to it as an object in the room that they appreciated seeing; specifically, how much they enjoyed the light reflecting on the plant. The diagram shown in Figure 4.4.6 illustrates the top ten terms most frequently used by participants while discussing their opinions of the scenes.


*Figure 4.4.6: Visualization of the most frequent terms participants used while discussing the scenes. The size of each term represents its frequency.*

Participants spoke about the overall design of the space: the wood floor, artwork, plant, shadows, lighting, window patterns, colors, and views to the outside. A surprising term that was used more than 50 times by 34 participants is “prison”. Two example sentences in which different participants used the term “prison” are: “This feels like a prison; it stresses me out”, and “I don’t like the window treatment; it reminds me of a prison”. Looking back at the spaces that led participants used the term “prison”, the skin design (or what the participant called a window treatment) in those spaces comprised either vertical slats or horizontal louvers. This result illustrates how strongly the design of everyday environments can affect occupants’ perception of and satisfaction with the spaces they inhabit.

The results of this experimental study also demonstrate that there is a clear association between participants’ satisfaction with brightness and other perceptual impressions, such as the access to the view outside, perceived pleasantness, interest, complexity and the overall ambiance. This indicates that our perception and satisfaction with brightness cannot be studied on its own without understanding how the overall design of the environment affects occupants' perception and visual impressions.

Our fitted regression model quantifies how people perceive brightness in a range of settings in which other perceptual attributes are varied while actual brightness is held constant. While we cannot directly control the perceptual impressions of people in a space, we can use this model to investigate how their satisfaction with brightness might change if we were able to design for the other attributes, again without changing the actual brightness of the scene. To do this, we used our fitted mixed effects model to investigate the satisfaction with brightness for a range of hypothetical scenarios, when all four other attributes are scored equally at levels ranging from 0 to 10. The relation between the two ratings indicates that the participants' satisfaction with brightness could potentially be shifted by five units, contrasting a building with minimal ratings on all other perceptual categories with a building with maximal ratings on all other perceptual categories. This result is important in the realm of design, especially in designing 'green' buildings, as post-occupancy surveys on occupants' satisfaction with lighting may be less related to the actual light levels and more to the overall quality and the ambiance of the building. Additional studies with a wider range of stimuli are needed to investigate the validity of the presented findings in different types of spaces, and with different brightness levels. Further research is encouraged to investigate the replicability of these results in a real environment.

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# Chapter 5
# **Discussion & Outlook**

In the design of building facades, their layers, materials, and composition affect daylight ingress, occupants' physiological and psychological wellbeing, and the overall energy demands of the interior. People like daylight inside buildings, as long as visual and thermal discomfort are prevented.

The effects of light on buildings' occupants have been studied for decades. Notably, in 1974, Ne'eman published an article on the "visual aspects of sunlight in buildings". In this article, he drew a distinction between light for visual activity or what he called "working-functional" light, and light that is needed for the "aesthetic-emotional" aspect of the environment (Ne'eman, 1974). The author further explained that while "working-functional" lighting can be provided by artificial or electric sources, the "aesthetic-emotional" effect is achieved by the interplay of daylight, the interior design and the surrounding materials and colors (Ne'eman, 1974).

It is noteworthy that in the last 45 years, focus has shifted to the "working-functional" aspects of light, and the "esthetic-emotional" aspects of daylight have mostly been overlooked in design. Similar to Cuttle (Cuttle, 2010), but more than four decades earlier, Ne'eman wrote, "…more and more artificially lit windowless interiors have been built. When occupants of such interiors have complaints, they are mostly not related to the functional-working lighting. They complain of insufficient emotional-psychological qualities of such environments" (Ne'eman, 1974).

Although the visual aspects of daylight have shown to have an immense impact on occupants' physiological and psychological wellbeing, current design practices do not adequately consider the visual aspects of daylight: its dynamics, shadow patterns, and the ways in which these are influenced by the building facade and the skin design.

Common daylight measuring methods and techniques focus on light availability on a two-dimensional workplane for task purposes and do not provide any information on human perception, nor provide a clear link between the simulation results and facade design. This shortcoming becomes a barrier for designers who seek to improve their design based on performance and blurs the line between subjective daylight appreciation and the association of daylight with visual discomfort, two concepts that should be differentiated. Most buildings are designed for people; therefore, their perception of and satisfaction with illumination is important in understanding how to create spaces that are both functional and energy efficient.

Research has shown that the human perception of the adequacy of illumination is strongly linked with lighting on vertical surfaces, and not on the horizontal plane (Love & Navvab, 1994). Studies have also suggested the use of the ratio of vertical illuminance to horizontal illuminance (VH ratio) as a performance indicator for daylighting systems in relation to indoor–outdoor illuminance ratios (Love & Navvab, 1994). Measuring the VH ratio can aid in evaluating human perception of lighting, as humans perceive relative, not absolute relative luminance values (Hopkinson, Petherbridge, & Longomore, 1966; Kittler, Kocifaj, & Darula, 2012). Although the VH ratio has been shown to be a strong indicator for comparing alternative window systems for daylight performance, the issue of linkage between measured data and the facade design remains; thus, it becomes difficult to identify and localize areas of the facade that do not perform adequately (either allowing too much or too little light to pass) and to adjust the design accordingly.

Another important criterion in lighting design is the directionality of incoming light. The VH ratio and the Virtual Lighting Laboratory (VLL) can be used to determine light's directionality. VLL is an image-based lighting analysis methodology which uses HDR digital images to extract per-pixel lighting information (M. N. Inanici & Navvab, 2006). VLL is a useful method that can provide information on luminance distribution and spatial lighting patterns by reading the RGB values of each pixel of an HDR scene. A difficulty with this method, however, is that it requires thousands of renderings as well as pixel-based image processing to fully understand the annual luminance distribution in a space, a difficult and computationally expensive process.

Facade Photometry is a key experimental outcome of this research study (see Chapter 4 Section 1 in this dissertation). It is a novel technique for efficiently measuring daylight infiltration through building facades. As a result of the sensors' arrangement on an imaginary hemisphere and their controlled FOV, annual spatial illuminance distribution through the facade can be measured at different gazing angles and directions. The resulting simulated data provide information on the presence or absence of direct sunlight, glare, peaks, vertical eye illuminance distribution, and directionality, and with a simple calculation, can be used to assess spatial luminance distribution and luminance contrast. The hemispherical sensor arrangement not only measures daylight infiltration through the facade, it also measures daylight reflected from the floor, ceiling and surrounding walls. Therefore, the spatial distribution of daylight measured can be used to ascertain the amount of light from different directions and gazing angles that reach an observer, and aid in visualizing the experience of that observer in the environment.

In a published research study on subjective responses to lighting by Wells, he noted, "without a single exception, before making a judgment, the subjects looked up and around: typically in the area half left to half right of the direction in which they were facing, i.e. in the direction of the windows" (Wells, 1965). Assessing light reflected off the surrounding surfaces measured by the sensors on the hemisphere is particularly useful not only in assessing visual discomfort associated with glare from the facade, but also in providing information on discomfort glare due to sources on peripheral visual field, an important indicator for evaluating facade performance and lighting design (Kent, Fotios, & Altomonte, 2019; Navvab & Altland, 1997). The new tool of Facade Photometry, developed as part of this dissertation research, is the only technique that directly connects the simulated data to the structure of the facade design, thus allowing designers to engage with the data and recognize the relationship between the design of the facade and its impact on interior lighting.

Quantifying light is important in architectural spaces to ensure that codes and standards are met, but understanding the end users of a space is also essential to ensure that the design is meeting their needs. As discussed above, light is needed for both the "working-functional" and "aesthetic-emotional" aspects of the visual environment; therefore, it is not only light quantity but also its quality that shapes and alters people's experience of a space. As a result of our contemporary lifestyle, most people spend more than 90% of their time indoors (Evans & McCoy, 1998), so it is increasingly important to construct spaces that maintain people's health, satisfaction, comfort and well-being.

Sadly, "there is little systematic information available about end users' opinions of the lighting they encounter" (Veitch, Hine, & Gifford, 1993). In a research study on the preferences of end users regarding lighting, the authors noted that the greater designers' understanding of end users' preferences for lighting, the more successfully they can communicate with the end users about the design (Veitch et al., 1993). Evaluating the effect of lighting on people is a complex endeavor. As the conceptual framework shown in Figure 5.1 illustrates, there are various elements and features of the environment that impact human and visual performance (Boyce, Hunter, & Howlett, 2003). A particularly important concept in the diagram is “Expectations”, which is listed as a component that affects “mood”, “motivation” and ultimately, “Human Performance”. Identifying the expectations of end users is pivotal, as their expectations impact their performance, preferences, and satisfaction with the environment.

The overarching intent of the Conceptual Content Cognitive Mapping (3CM) study described in Chapter 4 Section 2 was to identify end users’ perceptions, preferences and expectations of daylighting and to gain insight into what their needs related to daylight are, as well as how spaces could be better designed based on the future occupants’ preferences.

The results of this section provided a daylight lexicon that can be used for further qualitative studies and emphasized the terms that were frequently selected by the participants, such as “natural”, “connection to outside”, “sense of time and season”, “warmth”, “bright” and “energizing”. Additionally, the results externalized the mental model of both architects and non-architects on issues related to daylight in work environments. This highlighted the areas of disagreement between the two groups—concepts such as “uniformity”, “bright” and “sunny”. A visual relationship with the sun is often given the utmost priority in evaluating the psychological effect of daylight upon people (Ne’eman, 1974); therefore, concepts like “uniformity”, “brightness” and “sunny” need more recognition among researchers, and require further examination to ensure that spaces are designed effectively.

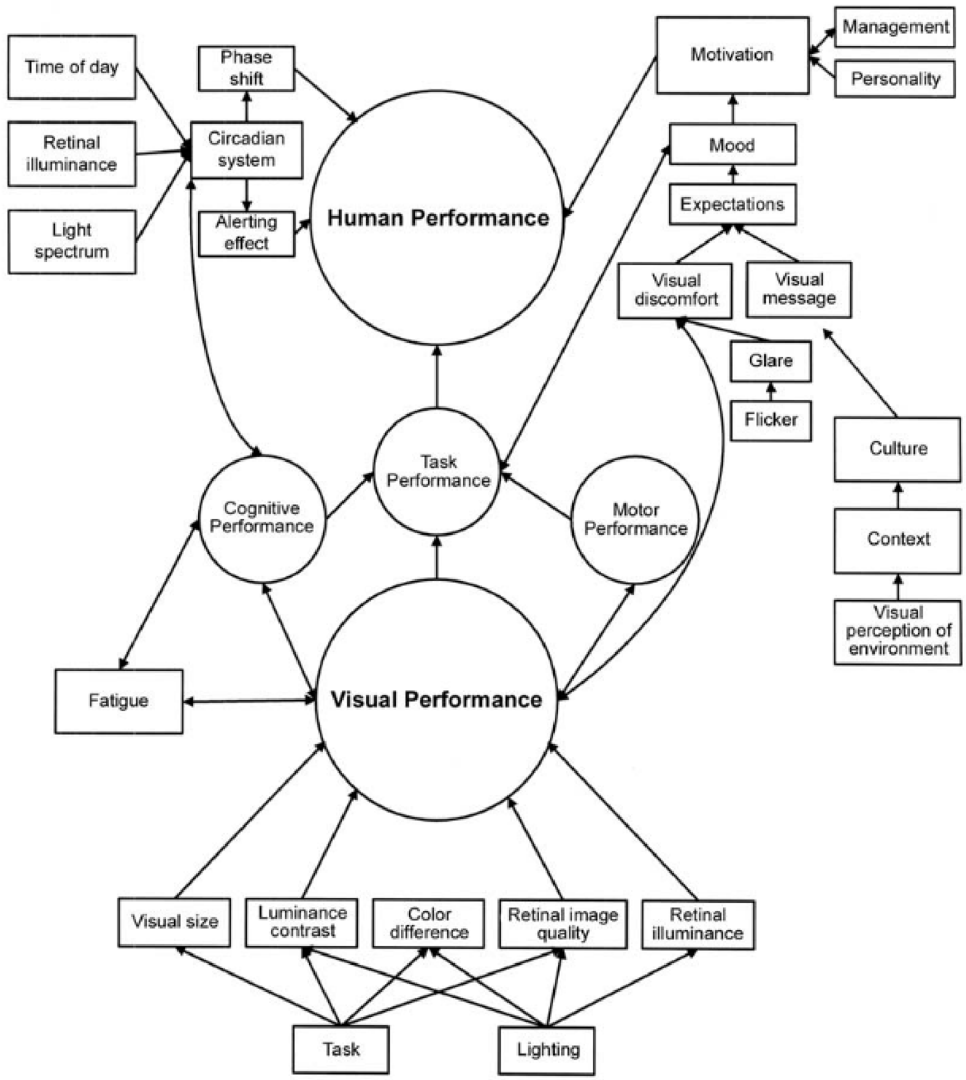


*Figure 5.1: "A conceptual framework setting out the routes by which lighting can influence human performance. The arrows indicate the direction of the effects." From Boyce et al.* (Boyce et al., 2003)

When a space does not provide the features its occupants need, the occupants will feel the lack. This may lead to dissatisfaction, as well a reduction in sense of well-being and overall performance within the space. The data analyses of this section confirmed that, in addition to the effect of daylight on human physiology (such as the production of hormone levels and circadian rhythm (M. Inanici, Brennan, & Clark, 2015; Leslie, Radetsky, & Smith, 2012)), daylight strongly affects people's feelings and emotions. This observation explains why majority of terms selected by participants in this experiment as important and relevant to effective design were related to the *psychological* effect of daylight in workspaces. Daylight is needed for visibility, but more importantly, it is needed because it provides a sense of connection to the outside world, a sense of warmth and happiness.

Earlier studies have found a discrepancy between the light level that is needed and that which is preferred (de Bakker, Aarts, Kort, van Loenen, & Rosemann, 2019); this discrepancy is one of the conundrums of space and lighting design, which must unify the photometric measurements with human emotions, perceptions and architectural aesthetics. In a research study on subjective responses to lighting, the author observed that participants' estimates about how much daylight they need is independent of the amount of daylight in the physical environment and is instead dependent on psychological judgments of apparent brightness distribution (Wells, 1965). A question that was put forward in the last sections of the study comprising this dissertation was: Is it solely the amount of light that contributes to occupants' perception and satisfaction of brightness? And do simulation choices such as the use of color and level of detail in the scenes to create the visual stimuli have an impact on occupants' perception of the space?

To address these questions and understand the effect of visual environment on participant's subjective impressions and satisfaction, an experimental study was conducted using an immersive virtual reality headset to investigate the effect of simulation choices such as the use of colors and furniture and the subjective impressions influencing brightness satisfaction. Chapter 4 Section 3 of this dissertation discussed the effect of simulation choices in creating virtual scenes, such as colors and furniture, on participants' subjective impressions.

By wearing an Oculus VR headset, the participants in this study (a total of 100 participants) observed six random scenes (out of a pool of 30 scenes) in grayscale, with partly colored, and with fully colored materials, both with and without furniture. Participants rated each scene by completing a verbal questionnaire. Statistical analyses of the data demonstrated a significant effect of colored materials on the impression of how pleasant, exciting and calming the spaces were perceived to be by participants. The use of colored material and how much they could see of the view outside also influenced participants' satisfaction with the brightness of each scene. With the exception of the attribute "calming", participants' evaluations of the scenes with color were more positive than of the same scenes presented in grayscale. Similarly, the level of detail associated with the presence of furniture significantly affected how participants rated the spaces as pleasant, exciting, interesting, calming and complex.

These findings have strong implications for research investigating people's subjective impressions of virtual environments. Thus, prior to utilizing environments that are simulated in research studies, it is important to determine the range of stimuli influencing participants' sensory and behavioral responses in those environments, as well to choose VR headsets capable of appropriately producing such environments (Hall, Navvab, Maslowski, & Petty, 2012). These findings strongly suggest that future research studies of simulated environments should devote special attention to the creation of the scenes used to ensure that simulation choices in regard to colors and detail do not adversely alter the subjective impressions and satisfaction of participants, and thus the accuracy and generalizability of the study's results. As Hall et al. indicated in their study of using virtual reality as a surrogate for sensory environment, "the fidelity of the simulation depends on the input data, the software, the display hardware, and the physical environment that houses it all" (Hall et al., 2012). The results of the study described in chapter 4 section 3 on the effect of simulation choices on occupant's evaluation of virtual environments demonstrated the attributes that were affected by the color and furniture in the scene, as well as those that were not influenced by the simulation factors. The outcome of this section can be used to direct future research on the use of color and furniture in simulated environments according to the attributes under investigation.

Chapter 4 Section 4 discussed the ways in which the subjective impressions of participants influence satisfaction with brightness. The aim of this experimental study was to evaluate if users' satisfaction with brightness is impacted by factors other than brightness levels. By holding the brightness level of all simulated scenes constant while varying the building skin's design, colors and furniture, the effect of different environmental factors on participants' brightness with satisfaction was examined.

The results demonstrated that participants' satisfaction with brightness is strongly linked with other perceptual attributes. Statistical analyses revealed a significant association between participants' satisfaction with brightness and how much they could see of the view outside, perceived pleasantness, interest, complexity and the overall ambiance. In addition to the impact of perceptual attributes on brightness satisfaction, the presence of color in the simulated scenes also influenced participants' satisfaction with brightness. The findings of this section of the research suggest that participants' perception and satisfaction of lit environments must not be evaluated without a clear understanding of how the design of the visual environment impacts their visual impressions. In fact, regression models of the composite data revealed that ratings of participants' satisfaction with brightness in scenes with the same brightness level could increase considerably by changing the design of the environment. Yet, in the last 100 years, our lighting codes and standards have increased substantially, not because humans have changed, but because lighting standards have increased to meet human expectations rather than meeting visual needs (Cuttle, 2017). If designing a more pleasant and interesting environment can shift the brightness satisfaction of the people that inhabit that space, then perhaps more effort and resources can be devoted to the overall design of the space, rather than excessive lighting.

The findings of this section of the research study may lead to considerable long-term energy savings if less electric light is used due to the overall design, while at the same time ensuring more people will be satisfied with the spaces they occupy. Therefore, recognizing the needs and behaviors of end users will aid in effective facade design and daylighting which will lead to long-term energy savings (Konis, K. and Selkowitz, 2017). An important takeaway from the outcome of this section is that perception of brightness is not always a direct result of the amount of light, but of the design of light, its flow, distribution, patterns and contrast.

Essentially, in the experimental study presented in Chapter 4-4, the building skin geometry, colors and level of details were the main driver in inducing impressions of the space, but this effect could be reproduced by other features of the space that affect the participants' perception of pleasantness, such as plants, colors, or materials—and this, too, could increase people's satisfaction with brightness in the space, without changing the actual light levels.

Some of the components in the scene that the majority of the participants expressed interest in during the open-ended question, were the plant, the shadow patterns on the plant and the wood floor (Figure 5.2).

*Figure 5.2: An image of an immersive scene showing a plant and shadow patterns on the wood floor.*

Participants repeatedly spoke about their appreciation of seeing the plant in the room and how much they enjoyed the light reflection and the shadow patterns in the space. Additionally, they spoke about their dislike of the vertical slats and horizontal louver design, indicating they triggered feelings of stress and confinement. What is astonishing about this outcome is that the most ubiquitous shading systems used today—vertical fins and horizontal louvers/blinds—are the two design options that participants noted they found confining, enclosed, boring, disconnecting, or simply put, prison-like.

The skin design clearly had an impact on the participants' perception and subjective ratings. Notably, it has been shown in a previous research study that facade design has a physiological impact on participants, as well as an emotional one (Chamilothori et al., 2019). This makes ever more pressing the question, how can we integrate the complexity of human perception, behavior, and expectations into effective design methods and processes? A well-daylit space is one that combines human comfort, health and perception (Andersen, 2015). Perhaps a new approach is required, one that starts with end users' wellbeing and quality of life, followed by best practices to design for efficient energy consumption and affordability.

The research work presented in this dissertation provides architects, designers and lighting researchers the ability to evaluate the performance of building facades more effectively in two ways. First, by development of a new tool for objective measurement of the distribution of daylight in a room after it has passed through a specific facade design. Second, by demonstrating the importance of perceived brightness on human wellbeing factors. This research also offers a protocol for evaluating the role of context (indoor features like form and color) on perceptions of brightness. Combined, these tools and new knowledge can be used by facade and light designers and researchers to evaluate a) indoor predicates of perceived brightness (the form and materiality of the lit space), b) users' perception of brightness and how they value this, and c) identify facade designs that simultaneously fulfill goals of human wellbeing and energy efficiency, two key aspects of sustainable design. Taken together, these results have the potential to empower designers in the decision-making process and allow them to engage more directly with their design to improve its overall performance, not only in regard to energy savings, but also occupants' satisfaction with the built environment.

Energy efficiency is, undoubtedly, an important design consideration, and often a key consideration of facade design. But designing for energy efficiency will only be effective if human comfort and wellbeing are accounted for. Indeed, the design of high-performance facades encompasses many conflicting objectives. For example, increasing daylight levels without proper precautions could greatly impact the total heat loss associated with the window-to-wall ratio. A high-performance building envelope design should provide effective and appropriate daylight, reduce the energy consumption of the building associated with cooling, heating and lighting, and provide a comfortable environment for its occupants. Sustainability is vital, but sustainability also requires the comfort and wellbeing of users. If an otherwise sustainable building is not comfortable to its users, it should not be able to claim this title: In uncomfortable "sustainable" buildings, sensors will be overridden, lights will be turned on while the shades are closed, and energy will be wasted. In a truly sustainable building, the quality of the user experience will not be a secondary concern.

Every day, people make judgements about the physical attributes of the environments they inhabit (Bar & Neta, 2006). The design features of these spaces influence the way in which they feel and behave. Architects and designers must consider: what are the features that evoke favorable evaluative response and how can we integrate these features in our design? What are the underlying mechanisms that explain how design variations influence the perception and preferences of occupants?

This research program confirms: the quality and success of a space's design is directly related to the quality and the quantity of light entering the space. Evaluating the quality of daylight requires an extensive knowledge of the impact of the facade design on both the daylight distribution and the occupants' comfort and wellbeing. Daylight is a perceptual issue; thus, the physical aspects of the light in a space on user's wellbeing and satisfaction must be addressed. Daylight is important in how spaces are perceived but bringing daylight into spaces doesn't require a wall with 100% glazing. As discussed in Chapter 4-4, brightness satisfaction isn't only a result of the quantity of light, but of the quality of the physical environment. A creative mind and a careful play of light and shadow is required to make inhabiting a space a pleasant experience.

## 5.1 Future Research

While this work offers support to those seeking to design spaces that meet the criteria discussed above, further interdisciplinary mixed methods research studies and experiments are required. Such studies will build a solid foundation upon which the complex interrelationship between design choices and their effects on human wellbeing can be further examined.

The overarching aim of future research will be to develop an integrative methodology that goes beyond creating energy efficient buildings to support the holistic design of sustainable environments that also supports occupants' wellbeing. Thus, it is vital to develop new methods of designing high-performance facades that promote the integration of formal building design with sustainable practices. The final research outcome will meet the criteria for design aesthetic and performance and will also have an impact on standard practice for benchmarking building performance within Leadership in Energy and Environmental Design.

Future research will investigate the relationship between spatial daylight measurements and subjective visual impressions and preferences. Similarly, additional subjective evaluation of daylight is required to gain insight into its dynamic quality and its effect on occupants' perception and preferences. The goal is to close the disconnect between measured environmental values, and users' sensory and perceptual experiences. To that end, the effect of building skin design on spatial daylight distribution will be examined to determine the ways in which daylight distribution can be linked to the intent of the skin design. Such studies will extend the use of the Facade Photometry technique to study visual discomfort associated with glare and assess if a correlation exist between simulated data and end users' comfort and preferences.

The outcome of each research study presented in this dissertation reveals new areas of research exploration that is essential for the improvement of future sustainable buildings. A topic of interest, currently under exploration, is the effect of blinds in patient rooms. Carefully designed facade optimizations often confront human comfort and privacy concerns in patient areas, especially around daylight and views. From an environmental perspective we want to design facades that maximize daylight and minimize energy use. From a patient experience perspective, we want to provide daylight, maximize views, provide visual comfort, and minimize glare. Often these objectives can be in direct conflict- resulting in patient rooms with large, beautiful views, where the blinds are constantly pulled down-effectively minimizing both the energy efficiency and human health and wellness goals. Thus, understanding blind usage can help us design facades in a predictive way that balances environmental and human outcomes. The results from the 3CM study, presented in Section 4-2, indicated a strong emotional connection that people have with natural light in spaces. Thus, in creating spaces, especially hospitals and patient rooms, facades need to be carefully composed to ensure that patients are fully connected with the outside world, have adequate view and daylight exposure without any visual discomforts. Facade Photometry offers the opportunity to measures daylight ingress in the position of the patient in the room. The results can be used to predict blind usage and minimize their use due to glare. This method aids designers working on new design projects but also in upgrading existing buildings. In addition to hospitals and patient rooms, large glass manufacturing companies are increasingly investigating ways to create facade systems that can reduce bird collision with glass. According to the American Bird Conservancy ("American Bird Conservancy", 2019), up to one billion birds die in America each year due to collisions with glass.  An effective solution to this unfortunate problem is adding patterns to the glazing so the birds can detect the glass. However,

as discussed in this research dissertation, the type and design of skin patterns greatly influence the daylight distribution and occupants' subjective impressions of the space. Thus, additional research is needed to examine the effects of specific design characteristics on occupants' subjective impressions. The results from Sections 4-3 and 4-4 of this dissertation creates a solid foundation to explore skin patterns that can have a positive impact on daylight distribution, occupants subjective impressions and consequently reduce bird collisions with glass.
Other areas of research will include examining the validity of data collected using Oculus VR headset in different types of spaces and brightness levels, as well as investigating the generalizability of these findings in a real environment. Furthermore, the effect of kinetic, automated skins and responsive glazing systems on occupants' health, comfort, and circadian rhythm could be effectively explored.

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# Appendices

# Appendix A:

## Image credits

**Chapter 1**

Figure 1.1:

Exterior of the Home Insurance Building by architect William Le Baron Jenney in Chicago, Illinois, built in 1885. Source: “This image is available from the United States Library of Congress's National Digital Library Program under the digital ID mhsalad.250058”

Found at:

https://en.wikipedia.org/wiki/Home_Insurance_Building#/media/File:Home_Insurance_Building.JPG

Figure 1.2:

Mies van der Rohe’s 860-880 Lake Shore Drive, Chicago, USA. Built in 1951

Source: © Jeremy Atherton, 2006.

Found at:

https://en.wikipedia.org/wiki/860%E2%80%93880_Lake_Shore_Drive_Apartments#/media/File:860-880_Lake_Shore_Drive.jpg

Figure 1.3:

a) Detail of mashrabiya, Maison es Suhaymi. Cairo, Egypt. Built in 1648. © Gérard Ducher. Wikimedia.

Found at: https://www.archdaily.com/510226/light-matters-mashrabiyas-translating-tradition-into-dynamic-facades

b) Carpenter Center for the Visual Arts, designed by Le Corbusier. Built in 1963. © Sanyam Bahga.

Found at: https://hiveminer.com/Tags/brisesoleil%2Clecorbusier

c) Al Bahr Towers, designed by AHR. Built in 2012. Credit: AHR

Found at: https://www.ahr.co.uk/Al-Bahr-Towers

Figure 1.4:

Undulating steel strips skin by Yoshihiro Amano.

Found at: https://www.amanod.com/jingumae

Figure 1.5:

John Lewis Department Store and Cineplex, Leicester. Farshid Moussavi

Found at:

https://www.farshidmoussavi.com/node/25#john_lewis_department_store_and_cineplex_leicester_25_25

**Chapter 2**

Figure 2.1:

An example of a complex building skin illustrating the difficulty of employing traditional shading systems such as overhang with these skins. Building: Suzhou Science and Cultural Arts Center. Studio 505. Architect Paul Andreu, Paris and ECADI, Shanghai—Facade Architect: dB(A)—Facade Engineer: ASSE Consultants

Found at: http://www.evolo.us/wp-content/uploads/2014/02/Suzhou-Science-and-Cultural-Arts-Center-Facade-Studio505-09.jpg

# Appendix B:

## 360° equirectangular stereoscopic renderings of the office scenes

Colored scenes with furniture

*Figure B. 1: Freshwater House, Chenchow Little, Sydney, Australia, 2008*

*Figure B. 2: Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002.*

*Figure B. 3: Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007*

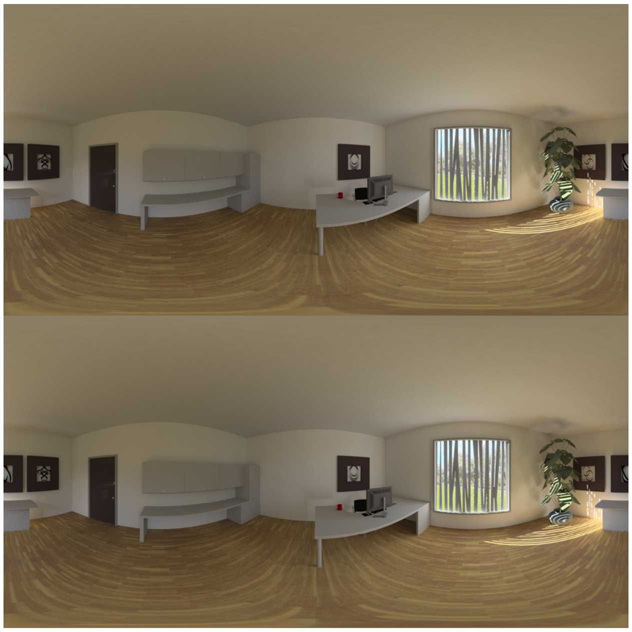

*Figure B. 4: Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013.*

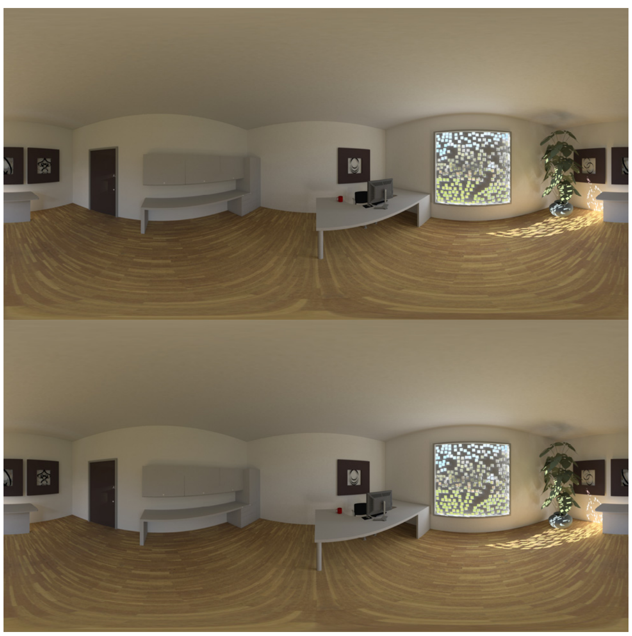

*Figure B. 5: Kew House, Piercy & Company, Richmond, United Kingdom, 2014.*

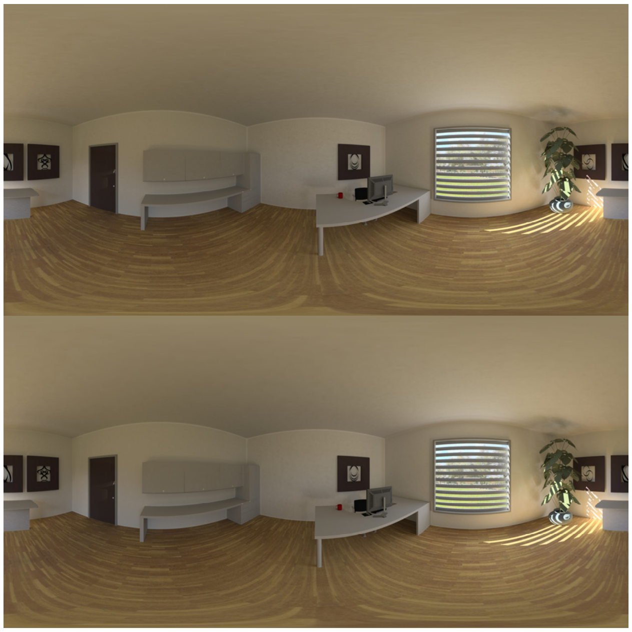

*Figure B. 6: Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012.*

Grayscale scenes with furniture

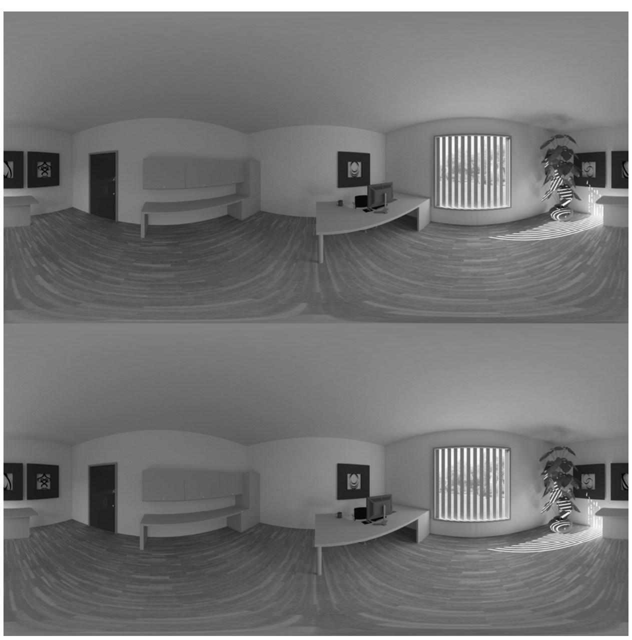

Figure B. 7: Freshwater House, Chenchow Little, Sydney, Australia, 2008.

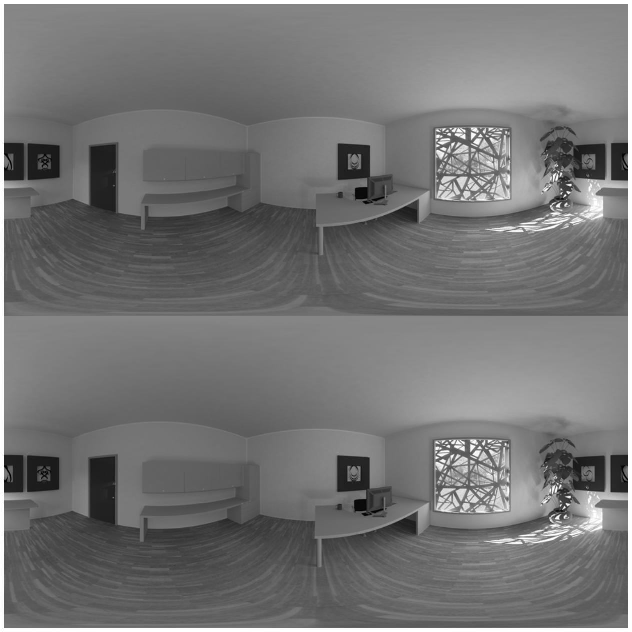

*Figure B. 8: Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002.*

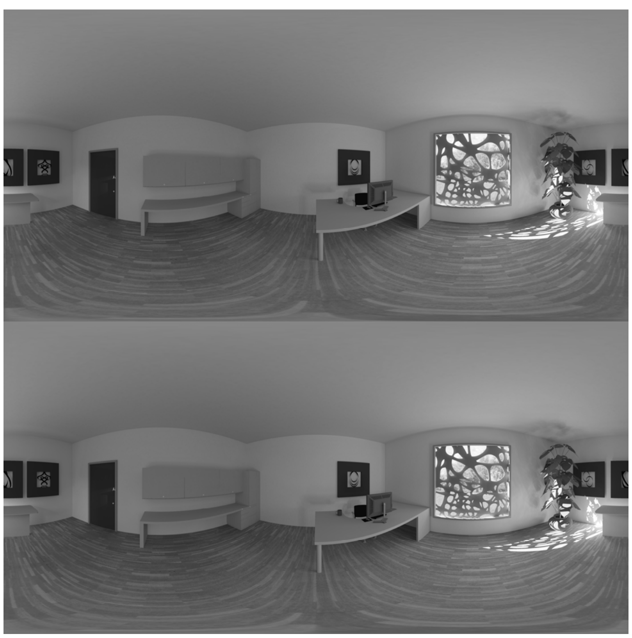

*Figure B. 9: Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

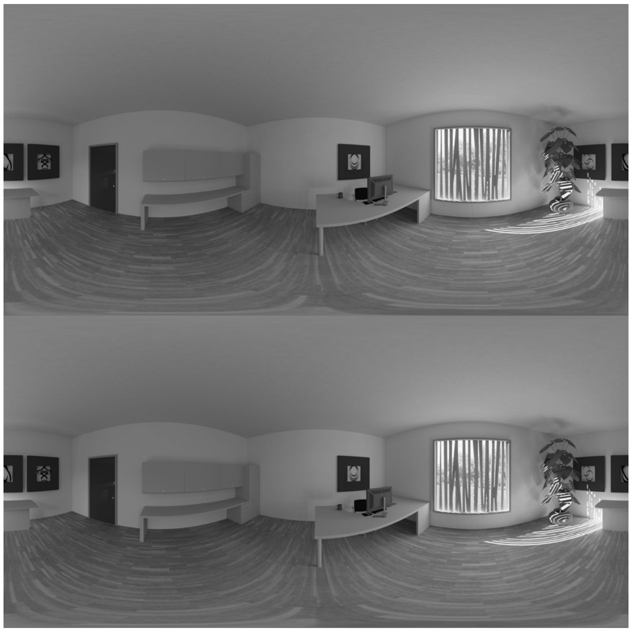

*Figure B. 10: Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013.*

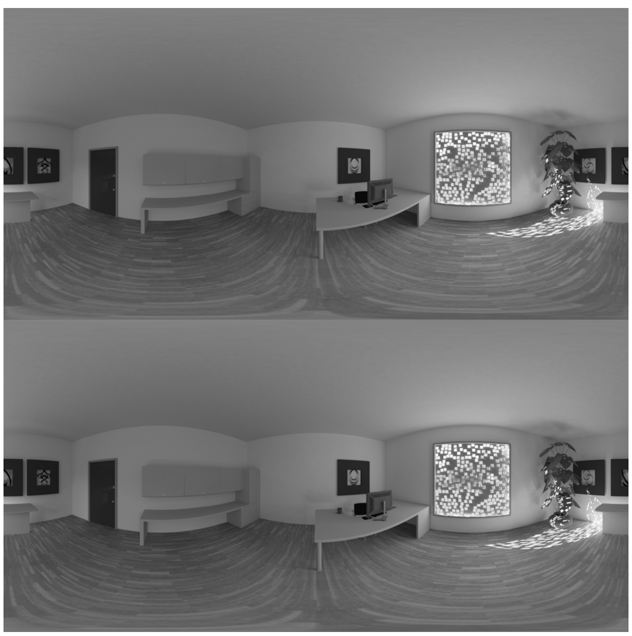

*Figure B. 11: Kew House, Piercy & Company, Richmond, United Kingdom, 2014.*

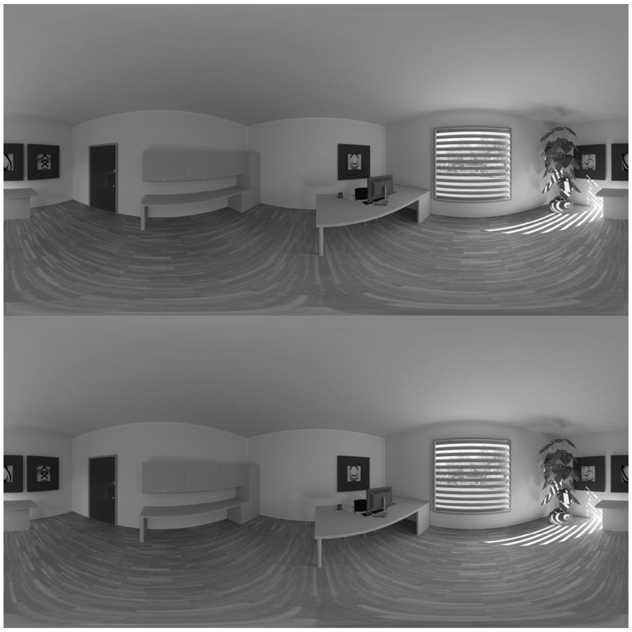

*Figure B. 12: Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012.*

Colored scenes without furniture

*Figure B. 13: Freshwater House, Chenchow Little, Sydney, Australia, 2008.*

*Figure B. 14: Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002.*

*Figure B. 15: Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

*Figure B. 16: Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013.*

*Figure B. 17: Kew House, Piercy & Company, Richmond, United Kingdom, 2014.*

*Figure B. 18: Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012.*

Grayscale scenes without furniture

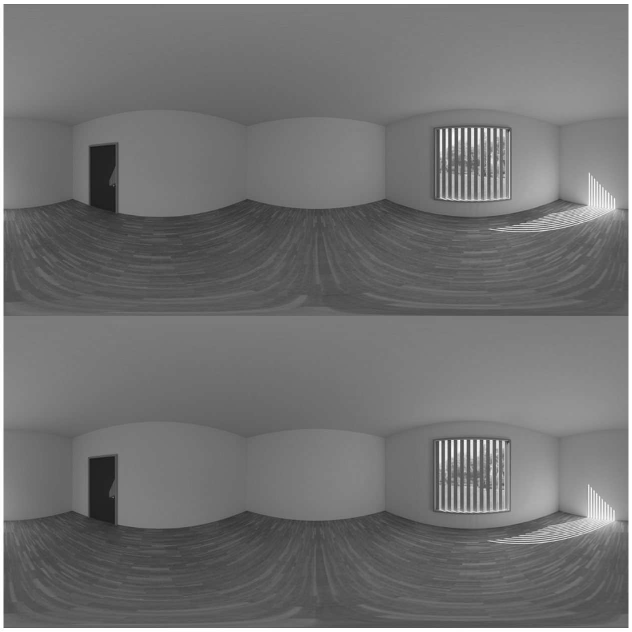

*Figure B. 19: Freshwater House, Chenchow Little, Sydney, Australia, 2008.*

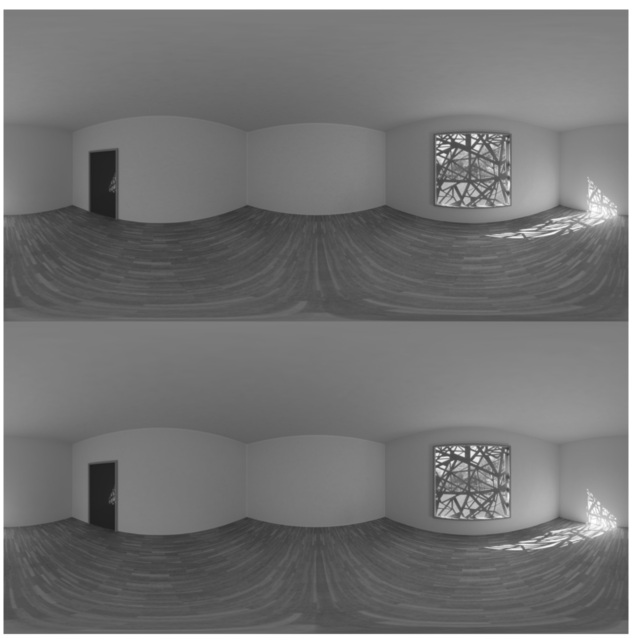

*Figure B. 20: Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002.*

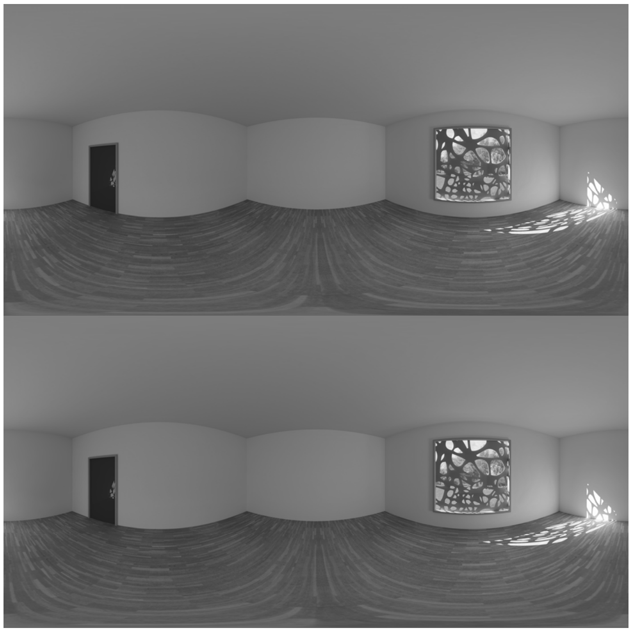

*Figure B. 21: Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

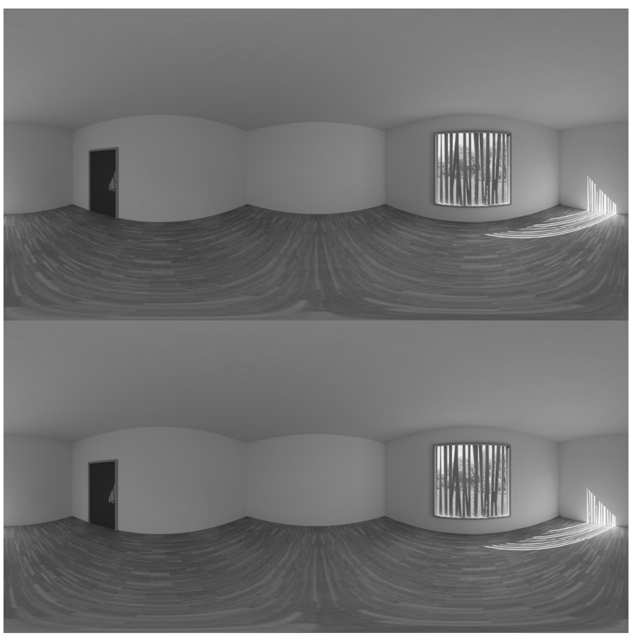

*Figure B. 22: Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013.*

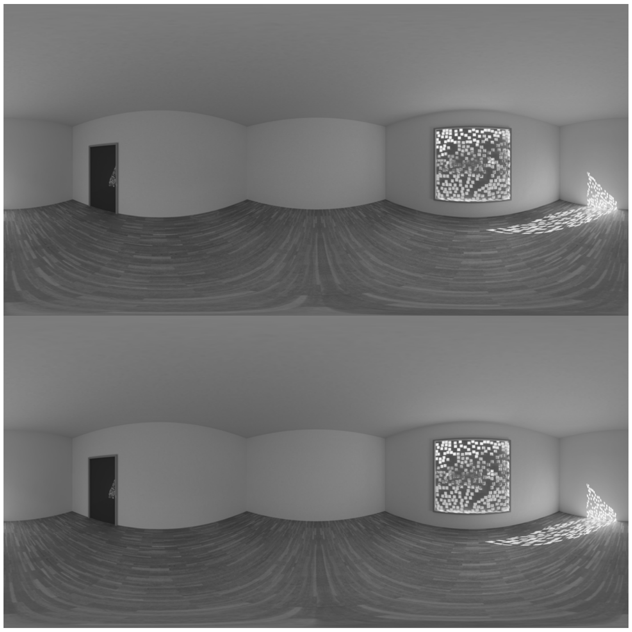

*Figure B. 23: Kew House, Piercy & Company, Richmond, United Kingdom, 2014.*

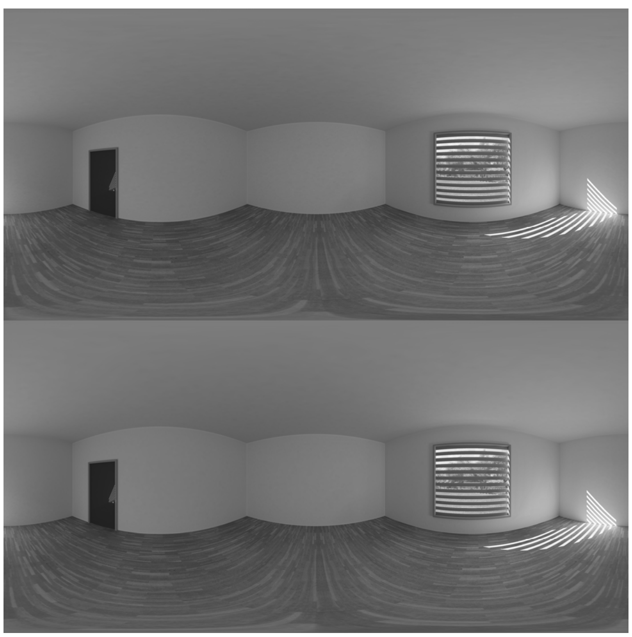

*Figure B. 24: Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012.*

Default scenes with furniture

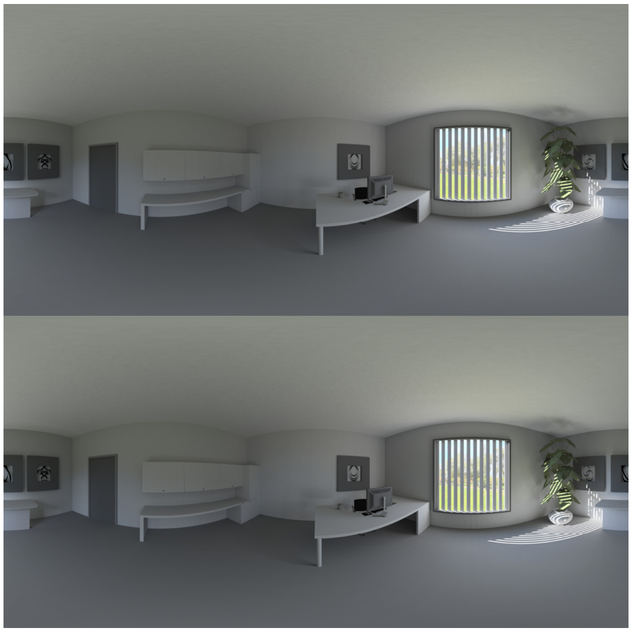

*Figure B. 25: Freshwater House, Chenchow Little, Sydney, Australia, 2008.*

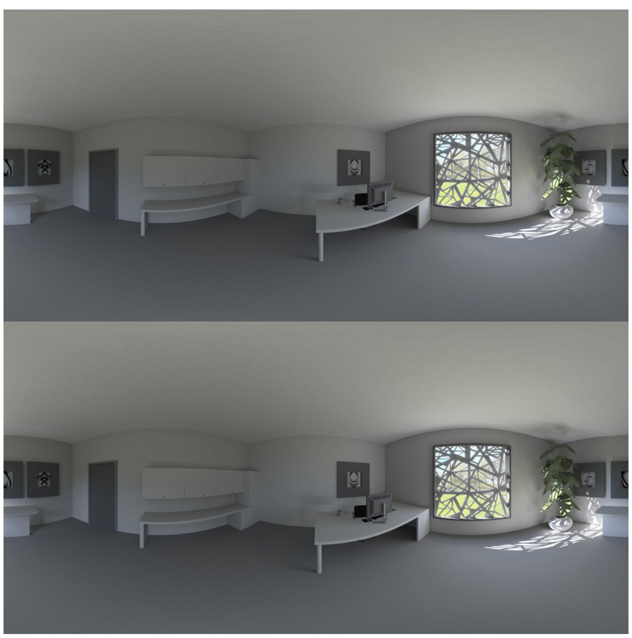

*Figure B. 26: Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002.*

*Figure B. 27: Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007.*

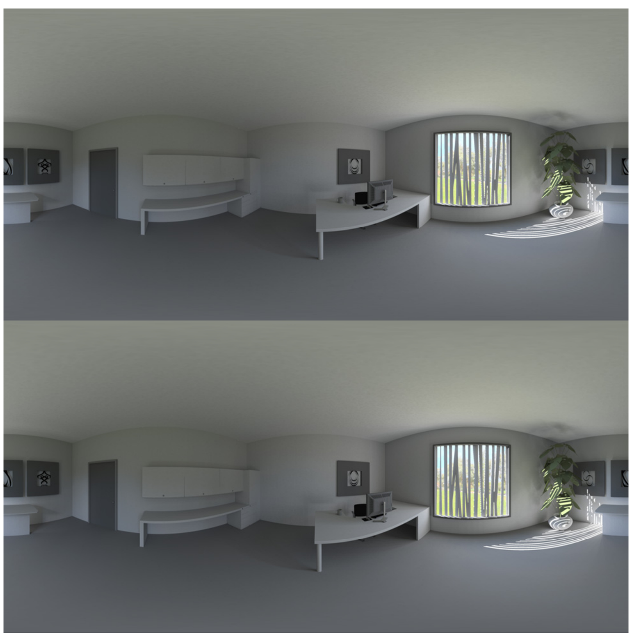

*Figure B. 28: Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013.*

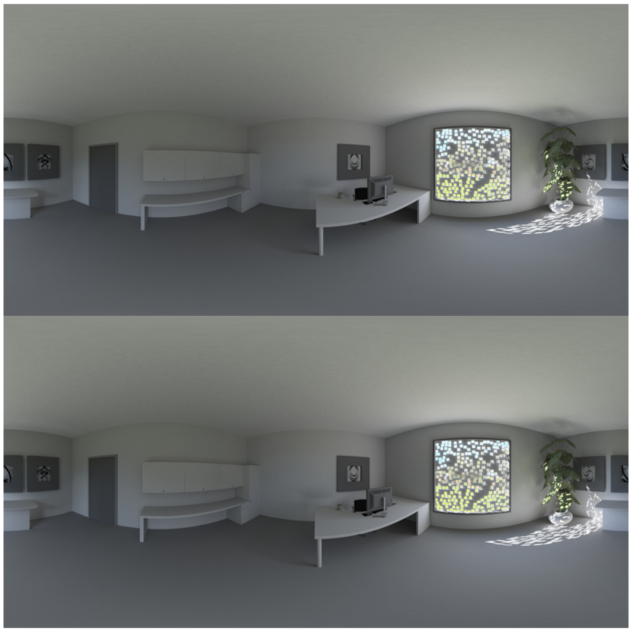

*Figure B. 29: Kew House, Piercy & Company, Richmond, United Kingdom, 2014.*

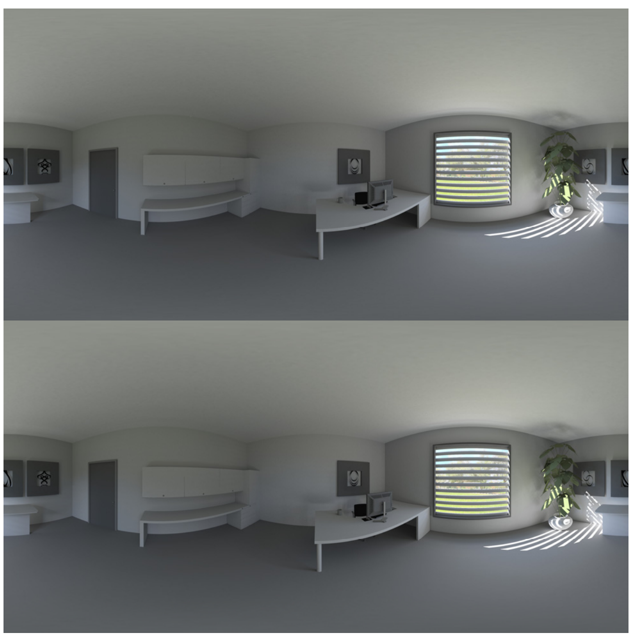

*Figure B. 30: Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012.*